

# New strong dynamics beyond the standard model

Lecture 4

21 November 2017

## Last time

- Partial compositeness results from linear mixing ( $\sim \lambda_q \bar{q} \mathcal{O}_q$ )  
between elementary fermions  $q$  and composite partners  $\mathcal{O}_q$
- Partial compositeness can provide viable EWSB potential for PNCB Higgs,  
with both non-zero vev  $\langle h \rangle \neq 0$  and  $\xi = \frac{v^2}{f^2} = \sin^2(\langle h \rangle / f) \ll 1$
- Partial compositeness allows high flavor scales  $\Lambda_F \sim 10^{13}$  GeV,  
if anomalous dimensions are large over a wide range of scales (near-conformality)
- UV completions describe dynamics behind strong  $\mathcal{G} \rightarrow \mathcal{H}$  symmetry breaking
- ‘Minimal’ UV completions have  $\mathcal{G} = \text{SU}(F)$  or  $\text{SU}(F) \times \text{SU}(F)$   
(no obvious UV completion for holography-based  $\text{SO}(5)/\text{SO}(4)$  MCHM)
- Incorporating partial compositeness requires non-minimal UV completion  
Baryon-like top partners best, most models have fermions in multiple reps

## Outline of experimental approaches

- Contrast **direct** searches vs. **indirect** constraints on  $\xi = \frac{v^2}{f^2} = \sin^2(\langle h \rangle / f)$   
Direct searches for new particles generally more robust but have less reach  
while indirect constraints generally have more reach but are less robust
- Three clear targets for **direct** searches: heavy vector; extra PNCBs; top partners
- Heavy vector like the  $\rho$  of QCD present even for minimal models, with  $M_V \simeq 4\pi f$   
Expect decays mostly to 2 (P)NCBs (i.e.,  $V_L V_L$ ,  $V_L H$ ), smaller rates to SM  $\psi \bar{\psi}$
- Extra PNCBs of non-minimal models ( $M_P \ll 4\pi f$ ) may also decay to dibosons  
Can anticipate that limits should be around recent transient excesses  
( $\sim 2$  TeV dibosons,  $\sim 750$  GeV diphotons)
- Assuming partial compositeness  $\rightarrow$  colored top partners with  $M_T \ll 4\pi f$
- Higgs couplings  $\rightarrow$  relatively new **indirect** constraints, still improving rapidly
- Constraints from precision EW observables ( $S$ ,  $T$ ) are still important,  
as are those from high-precision flavor physics (e.g.,  $D-\bar{D}$  mixing, CP violation)

## Direct searches for heavy vectors and PNGBs

- Many models and [many searches](#)  $\rightarrow$  experiments run simplified analyses for theorists to translate into bounds on particular models
- Recall some complications of **hadron colliders**:
  - Don't have control over  $\sqrt{s}$  of colliding partons—have to integrate over pdfs
  - Complicated debris in detectors from underlying event and pileup
  - Very large background rates require discarding almost all events via trigger
- $\rightarrow$  Increasing  $\sqrt{s}$  can have [big effects](#) on production cross sections
- [Diboson constraints](#) reach  $\sim 3$  TeV, for  $\sqrt{s} = 8$  & 13 TeV (as of ICHEP2016)  
Using NDA expectation  $M_V \simeq 4\pi f \rightarrow f \gtrsim 240$  GeV gives no constraint,  
but scaling up QCD  $M_\rho/f \simeq 8$  suggests  $f \gtrsim 375$  GeV  $\rightarrow \xi \lesssim 0.43$
- If non-minimal PNGBs  $\pi^a$  with  $M_P \ll 4\pi f$  can decay to dibosons,  
then constraints are [more significant](#):  $f_\chi \gtrsim 500$  GeV  $\rightarrow \xi \lesssim 0.24$  for color octets
- PNGBs decay to dibosons through [WZW terms](#)  $\sim c^{abc} \pi^a \epsilon^{\mu\nu\alpha\beta} A_{\mu\nu}^b A_{\alpha\beta}^c$   
 $\rightarrow$  width  $\Gamma \propto M_P^3/f^2$  compared to  $\Gamma \propto M_P M_t^2/f^2$  for decays to  $t\bar{t}$
- **Warning**: Many diboson searches use a **narrow width approximation**,  
assuming  $\Gamma \ll M$  ([typically](#) percent-level  $\Gamma/M$ ) among [other conditions](#)  
This is problematic for QCD-like  $\Gamma_\rho/M_\rho \approx 150/770 \approx 0.19$ ,  
and larger  $\Gamma/M$  lead to [weaker constraints](#)

## Direct searches for top partners $T$

- Expect [colored resonances](#) may be easier to produce at LHC  
Due to phase space, [single  \$T\$  production](#) (with  $b$  or  $t$ ) preferred for  $M_T \gtrsim 750$  GeV,  
despite suppression by  $W$ ,  $Z$  exchange
- With same caveats as above, [current bounds](#) are  $M_T \gtrsim 800$  GeV  
MCHM<sub>5</sub> analyses  $\rightarrow f \gtrsim 600$  GeV ( $\xi \lesssim 0.17$ ) to produce correct Higgs mass
- Experimental results include searches for exotically charged  $X_{5/3} \rightarrow W^+ t$

## Higgs couplings

- In lecture 2 we derived  $\kappa_{VVh} \equiv \frac{g_{VVh}^{\text{SM}}}{g_{VVh}} = \sqrt{1 - \xi}$  for Higgs coupling to  $V = W, Z$
- Partial compositeness  $\rightarrow$  similar ratios  $\kappa_F \equiv \frac{g_{F\bar{F}h}}{g_{F\bar{F}h}^{\text{SM}}}$  for fermions

Despite dependence on rep(s) of  $\mathcal{O}_F$ , **two common patterns**:

$$\kappa_F^A = \sqrt{1 - \xi} \approx 1 - \frac{1}{2}\xi \qquad \kappa_F^B = \frac{1 - 2\xi}{\sqrt{1 - \xi}} \approx 1 - \frac{3}{2}\xi \qquad (1)$$

(MCHM<sub>4</sub>  $\rightarrow$  A; MCHM<sub>5</sub>, NMCHM, Georgi–Kaplan coset  $\rightarrow$  B)

- $\kappa_F \lesssim 1$  reduces Higgs cross section, but also branching fractions to fermions  
Together these two effects can account for SM-like observations at the LHC
- **Higgs couplings** down to  $\tau$  measured to be within  $\mathcal{O}(10\%)$  of SM values  
For MCHM<sub>4/5</sub> find  $\xi < 0.2 \rightarrow f = v/\sqrt{\xi} \gtrsim 550$  GeV from LHC Run I
- Can also define  $\kappa_g$  and  $\kappa_\gamma$  for effective  $hgg$  and  $h\gamma\gamma$  couplings  
If **only one dominant top partner**, its effects cancel in  $\kappa_g$  [ $\kappa_g = (\kappa_F^B)^2$  in MCHM<sub>5</sub>]  
(special feature of PNGB composite Higgs, in contrast to supersymmetric models)
- **Combined analysis** of LHC Run II results available in early 2017 finds  
model-independent limit  $f \gtrsim 500$  GeV at 95% CL, tighter for certain cases
- $\sim 10\times$  **improved precision** may be possible  
from future  $e^+e^-$  “Higgs factories” with cleaner environments

## Precision electroweak observables ( $S$ and $T$ parameters)

- Can be **three distinct contributions** to  $S$  and  $T$
- **First**, recall we subtract the standard model contributions from  $S$  and  $T$ ,  
removing chiral-log divergences of eaten NGBs and SM Higgs
- Modified Higgs couplings **reintroduce** those logs,  $\propto \xi \log\left(\frac{\Lambda^2}{M_H^2}\right)$ ,  $\Lambda = 4\pi f$  or  $M_V$
- Extra PNGBs in non-minimal models can also add similar chiral logs,  
depending on how they transform under  $SU(2)_L \times U(1)_Y$
- This ‘IR’ contribution is positive for  $S$  but negative for  $T$

## Precision electroweak observables (continued)

- **Second**, in lecture 2 we derived a dispersion relation for the  $S$  parameter,

$$S = 4 \int \frac{ds}{s} \text{Im} [\Pi'_{VV}(s) - \Pi'_{AA}(s)]_{\text{new}} = \frac{1}{3\pi} \int \frac{ds}{s} [R_V(s) - R_A(s)]_{\text{new}}$$

- In the **large- $N$  limit**, can approximate  $R(s)$  as sum of narrow poles

Keeping only first pole in each channel,  $R(s) \rightarrow 12\pi^2 F^2 \delta(s - M^2)$ ,

$$\text{gives crude approximation } \Delta S \simeq 4\pi \left[ \frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right] > 0$$

- Sign follows from Weinberg sum rules (due to  $\Pi_{V-A}(Q^2) \sim 1/Q^4$  as  $Q^2 \rightarrow \infty$ )

$$\begin{aligned} \int ds [R_V(s) - R_A(s)] &= 12\pi^2 F_P^2 & \int ds s [R_V(s) - R_A(s)] &= 0 \\ \longrightarrow F_V^2 - F_A^2 &= F_P^2 > 0 & F_V^2 M_V^2 - F_A^2 M_A^2 &= 0 \end{aligned}$$

- Custodial symmetry  $\longrightarrow$  this ‘vector’ contribution to  $T$  vanishes at leading order
- **Finally**, loops of top partners also contribute  $\Delta S \propto \xi \log \left( \frac{\Lambda^2}{M_T^2} \right)$  and  $\Delta T \propto y_t^2 \xi$
- This fermion contribution to  $S$  is again positive, and it can be positive for  $T$  as well
- With some model dependence, need  $\xi \lesssim 0.1$  to remain consistent with experiment

## Flavor constraints

- Start from **UTFit Collaboration** bounds on  $\Delta F = 2$  coefficients:

$$\begin{aligned} |\text{Re}[C_K]| &\lesssim 9.6 \times 10^{-13} \text{ GeV}^{-2} & |C_D| &\lesssim 7.2 \times 10^{-13} \text{ GeV}^{-2} \\ |C_B| &\lesssim 2.3 \times 10^{-11} \text{ GeV}^{-2} & |C_{B_s}| &\lesssim 1.1 \times 10^{-9} \text{ GeV}^{-2} \end{aligned}$$

Stronger bound  $|\text{Im}[C_K]| \lesssim 4.4 \times 10^{-15} \text{ GeV}^{-2}$  relevant if new strong CP violation

- For bilinear case  $C \sim 1/\Lambda_F^2$ , **these lead to**  $\Lambda_F^{(c)} \gtrsim 1500 \text{ TeV}$  from  $D-\bar{D}$  mixing  
and  $\Lambda_F^{(s)} \gtrsim 10,000 \text{ TeV}$  from CP violation in strange sector
- Although partial compositeness allows a high flavor scale  $\Lambda_F \gtrsim 10^{13} \text{ GeV}$ ,  
it also introduces **flavor-dependent** couplings around  $4\pi f$  scale
- But four mixings  $\longrightarrow$  suppression by  $\lambda_i \lambda_j \lambda_i \lambda_j \sim y_i y_j \sim m_i m_j / v^2 \gtrsim 10^{-5}$   
(worst case is  $\sim 0.1 \cdot 5/246^2$  for  $B_s$ )
- A TeV-scale  $4\pi f$  requires more suppression (e.g., a GIM-like mechanism)  
Generically need to tune  $4\pi f \gtrsim 10 \text{ TeV}$   
 $\longrightarrow f \gtrsim 800 \text{ GeV}$  or  $\xi \lesssim 0.1$  comparable to constraints from Higgs couplings

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1 - 4 j$	Yes	36.1	$M_D$ 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	-	$2 j$	-	37.0	$M_{\text{th}}$ 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\Sigma p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK} \text{ mass}$ 4.1 TeV	$k/\bar{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\nu$	$1 e, \mu$	$1 J$	Yes	36.1	$G_{KK} \text{ mass}$ 1.75 TeV	$k/\bar{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	$KK \text{ mass}$ 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$	ATLAS-CONF-2016-104	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z' \text{ mass}$ 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z' \text{ mass}$ 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	3.2	$Z' \text{ mass}$ 1.5 TeV		1603.08791
	Leptophobic $Z' \rightarrow tt$	$1 e, \mu, \geq 1 b, \geq 1 J/2 j$	Yes	3.2	$Z' \text{ mass}$ 2.0 TeV		$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	36.1	$W' \text{ mass}$ 5.1 TeV		1706.04786
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}q$ model B	$0 e, \mu$	$2 J$	-	36.7	$V' \text{ mass}$ 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V' \text{ mass}$ 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	20.3	$W' \text{ mass}$ 1.92 TeV		1410.4103	
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	$W' \text{ mass}$ 1.76 TeV		1408.0886	
CI	CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV	$\eta_{LL}^-$	1703.09217
	CI $\ell\ell qq$	$2 e, \mu$	-	-	36.1	$\Lambda$ 40.1 TeV	$\eta_{LL}^-$	ATLAS-CONF-2017-027
	CI $uu\ell\ell$	$2(SS)/\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	20.3	$\Lambda$ 4.9 TeV	$ C_{RR}  = 1$		1504.04605
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	$m_{\text{med}}$ 1.5 TeV	$g_q=0.25, g_\nu=1.0, m(\chi) < 400 \text{ GeV}$	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$\leq 1 j$	Yes	36.1	$m_{\text{med}}$ 1.2 TeV	$g_q=0.25, g_\nu=1.0, m(\chi) < 480 \text{ GeV}$	1704.03848
	VV $\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	$M_\chi$ 700 GeV	$m(\chi) < 150 \text{ GeV}$	1608.02372
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$0 \text{ or } 1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	13.2	$T \text{ mass}$ 1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \rightarrow Zt + X$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	36.1	$T \text{ mass}$ 1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	1705.10751
	VLQ $TT \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$T \text{ mass}$ 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	20.3	$B \text{ mass}$ 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1 b$	-	20.3	$B \text{ mass}$ 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	1409.5500
	VLQ $BB \rightarrow Wt + X$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$B \text{ mass}$ 1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	CERN-EP-2017-094
VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	$Q \text{ mass}$ 690 GeV		1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	37.0	$q^* \text{ mass}$ 6.0 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^* \text{ mass}$ 5.3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	13.3	$b^* \text{ mass}$ 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1 b, 2-0 j$	Yes	20.3	$b^* \text{ mass}$ 1.5 TeV	$f_d = f_s = f_b = 1$	1510.02664
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	LRSM Majorana $\nu$	$2 e, \mu$	$2 j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm} \text{ mass}$ 870 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV		1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$	1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g  = 1g_D, \text{spin } 1/2$	1509.08059

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

†Small-radius (large-radius) jets are denoted by the letter j (J).

Figure 1: Summary of mid-2017 constraints from searches for relatively generic ‘exotic’ particles by ATLAS. Constraints that may be relevant to composite Higgs models include the heavy vector triplet (HVT) bound  $M_V \gtrsim 3 \text{ TeV}$ , vector-like quark (VLQ) bounds  $M_T \gtrsim 1 \text{ TeV}$ , and Higgs triplet bounds  $M_{\pi^a} \gtrsim 400 \text{ GeV}$ . More summary plots and future updates are published [online](#), as are similar public results from [CMS](#).

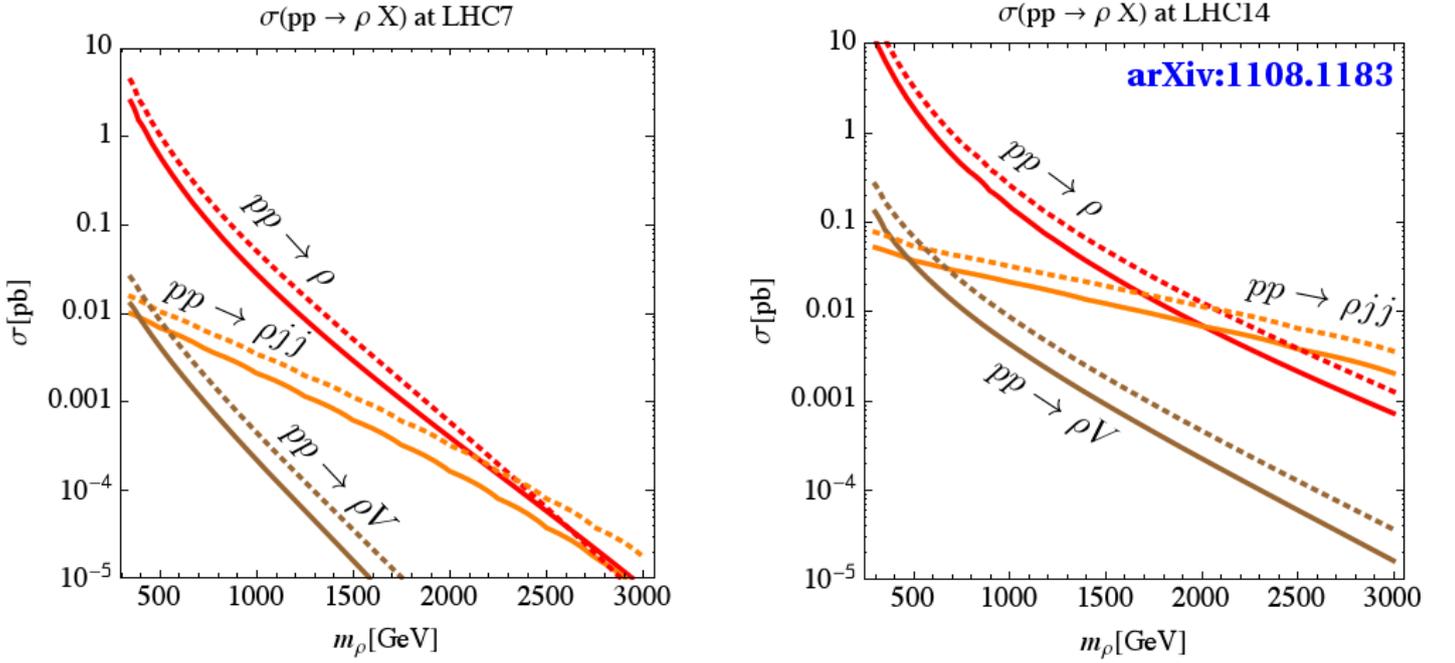


Figure 2: LHC production cross sections for a single charged (dotted) or neutral (solid) heavy vector boson ‘ $\rho$ ’, in the Drell–Yan (red), vector-boson-fusion (orange) and  $\rho$ -strahlung (brown) channels, from [arXiv:1108.1183](https://arxiv.org/abs/1108.1183). The larger  $\sqrt{s} = 14$  TeV (right) significantly enhances the cross sections for large  $m_\rho \gtrsim 2$  TeV compared to  $\sqrt{s} = 7$  TeV (left).

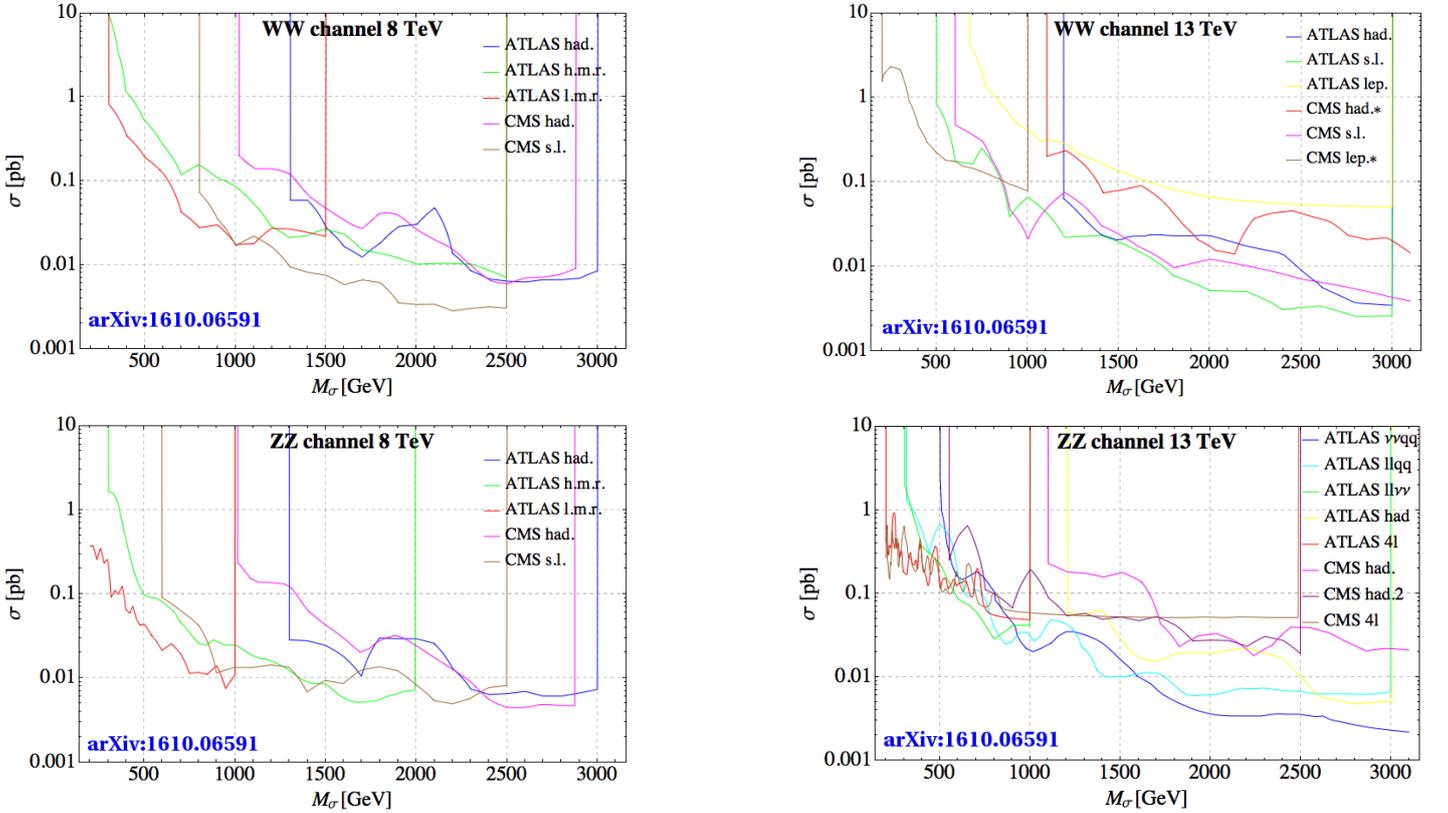


Figure 3: LHC bounds on cross section  $\times$  branching fraction for  $WW$  (top) and  $ZZ$  (bottom) final states, from multiple 8 TeV (left) and 13 TeV (right) LHC searches, collected in [arXiv:1610.06591](https://arxiv.org/abs/1610.06591).

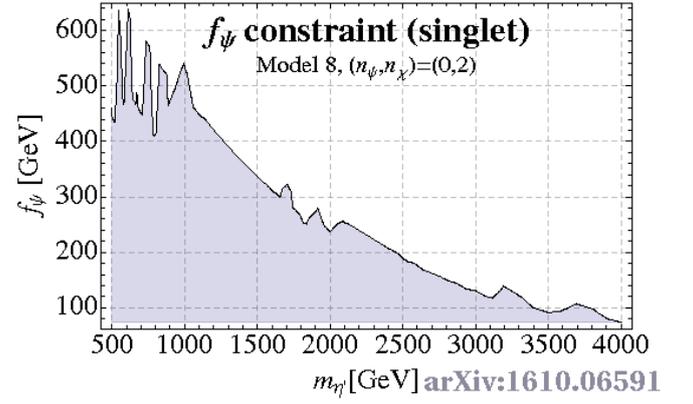
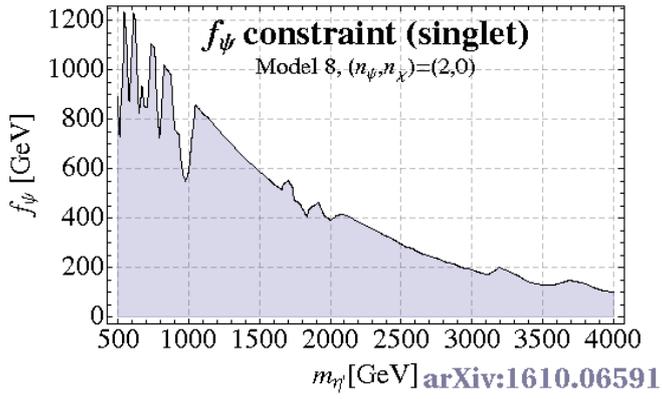
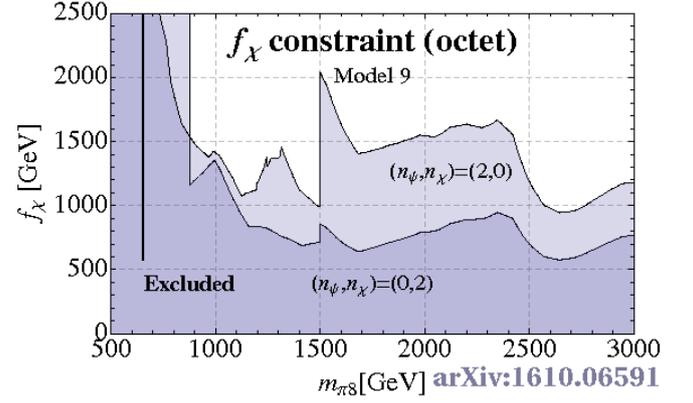
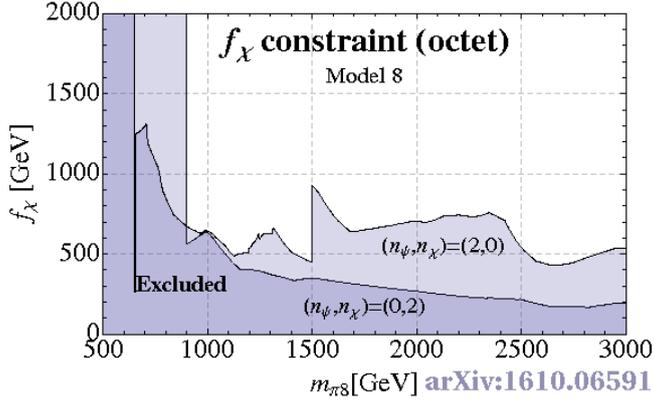


Figure 4: Constraints from [arXiv:1610.06591](https://arxiv.org/abs/1610.06591) on the two symmetry breaking scales  $f$  in two non-minimal composite Higgs models based on multi-rep partially composite UV completions, using the diboson bounds in the previous figure along with other LHC data. The  $\chi$  fermions carry QCD color while the  $\psi$  fermions carry EW quantum numbers, enabling stronger constraints on  $f_\chi \gtrsim 500$  GeV (top) compared to  $f_\psi$  (bottom, for different charge assignments in a single model).

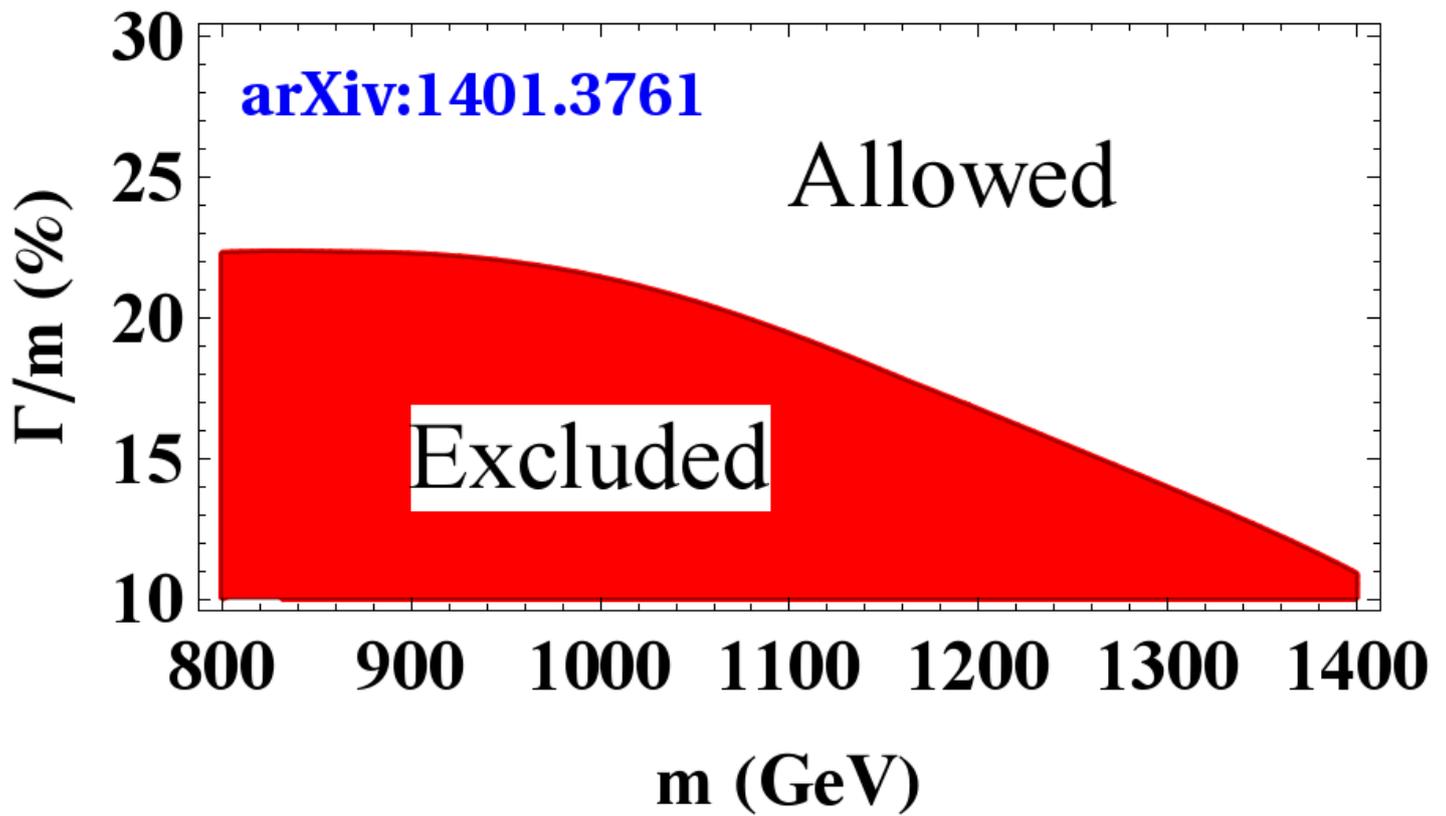


Figure 5: Illustration of how LHC constraints on heavy vectors become weaker as the width  $\Gamma$  of the new resonance increases compared to its mass  $m$ , from [arXiv:1401.3761](https://arxiv.org/abs/1401.3761). The data being considered come from [CMS-PAS-EXO-12-025](https://arxiv.org/abs/1202.4236), a search for  $W' \rightarrow WZ \rightarrow \text{leptons}$  based on 19.6/fb of  $\sqrt{s} = 8$  TeV data.

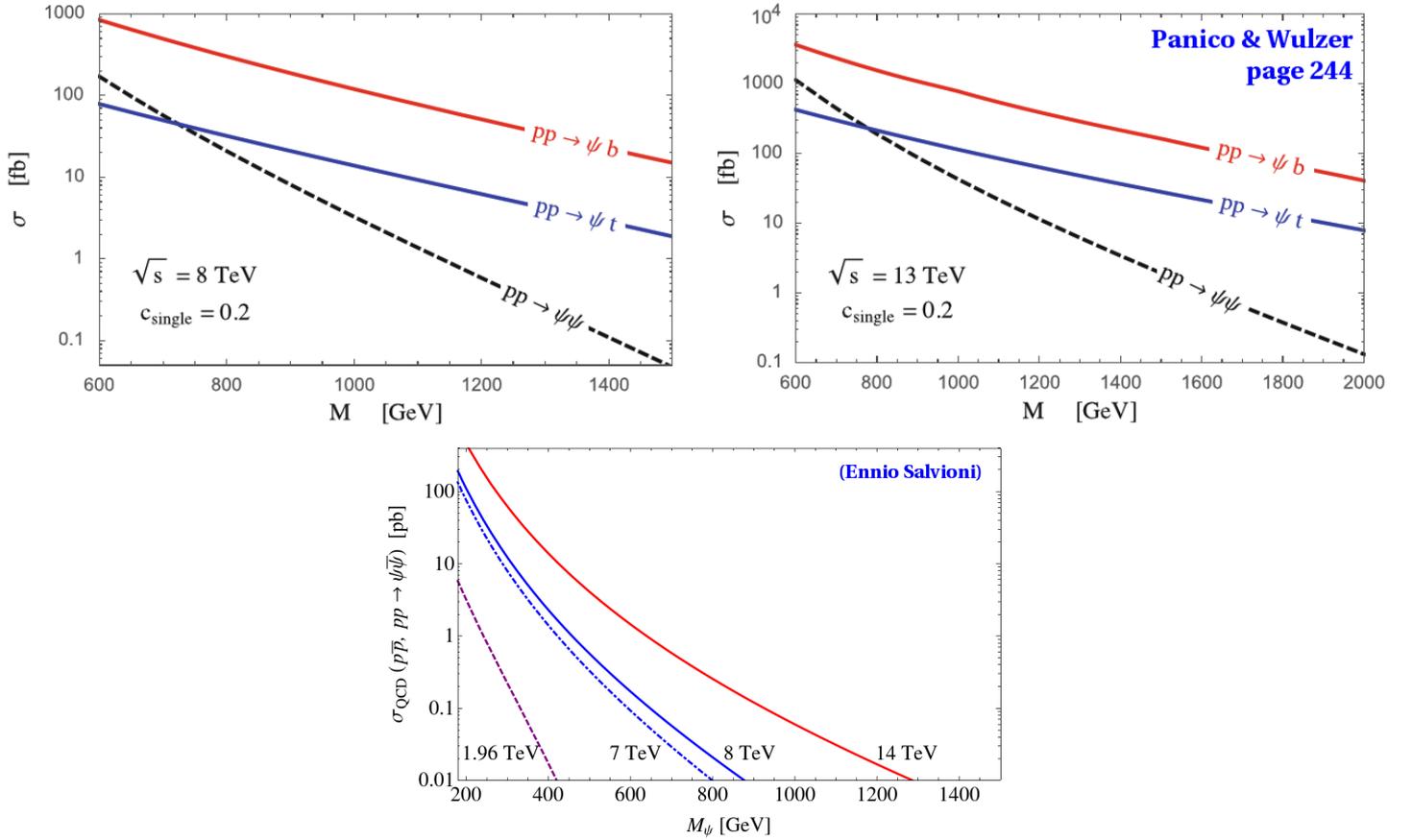


Figure 6: **Top:** LHC production cross sections for either one or two top partners  $\psi$ , with  $c_{\text{single}} = g_2\sqrt{\xi} \approx 0.65\sqrt{\xi}$ . For  $M_\psi \gtrsim 750$  GeV the larger top partner mass leads the pair-production cross section to fall below the single-production cross section. **Bottom:**  $\psi\psi$  pair production cross sections for Tevatron and LHC energies, from [Ennio Salvioni](#), showing the large enhancements possible from larger  $\sqrt{s}$ .

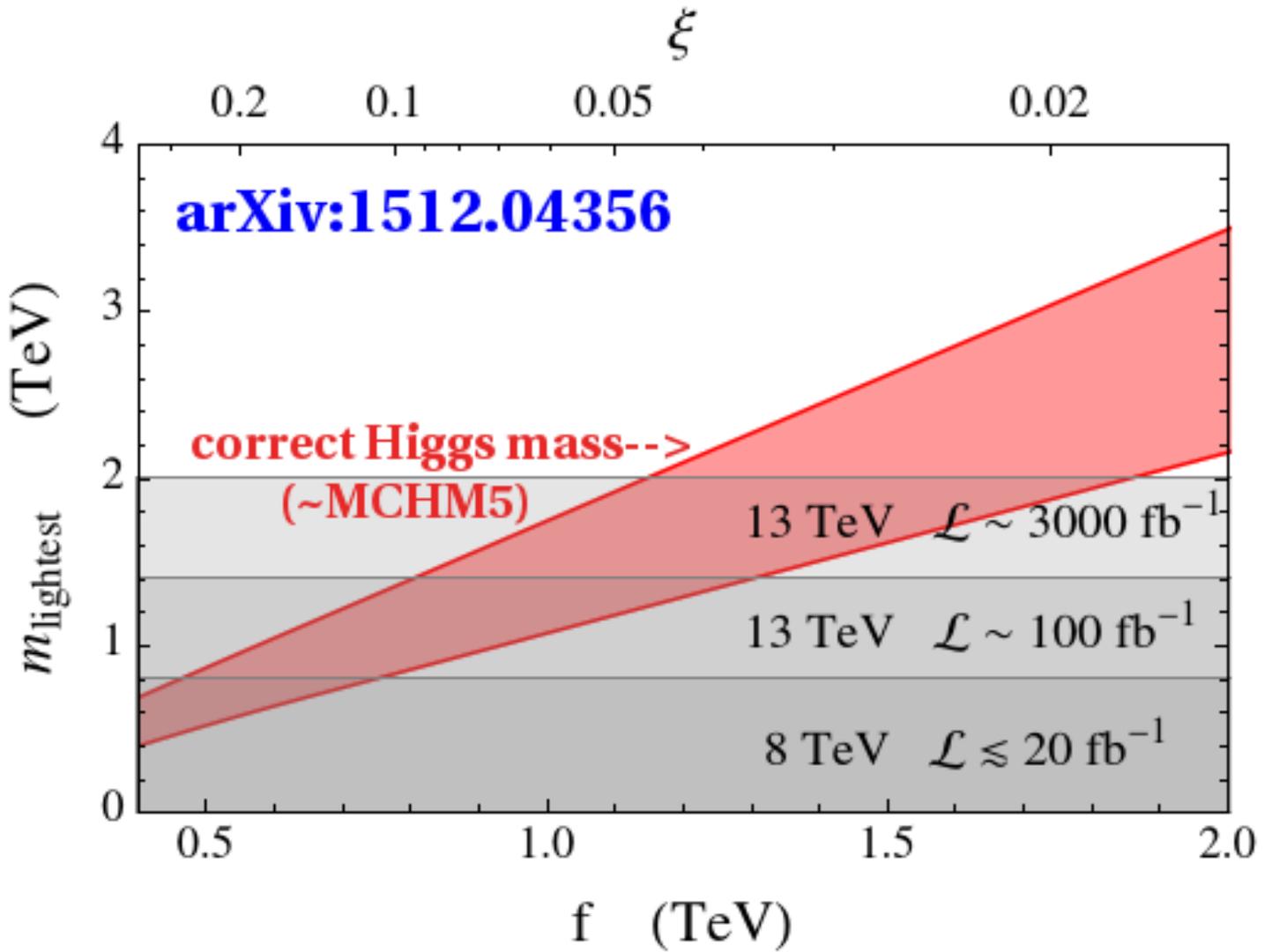


Figure 7: Current and projected LHC constraints on the lightest top partner mass in the MCHM<sub>5</sub> (typically an exotically charged  $X_{5/3}$ ), from [arXiv:1512.04356](https://arxiv.org/abs/1512.04356). The red band estimates (with  $\sim 20\%$  precision to account for approximations in the analyses) the corresponding symmetry breaking scale  $f$  that should produce the correct Higgs mass in this model.

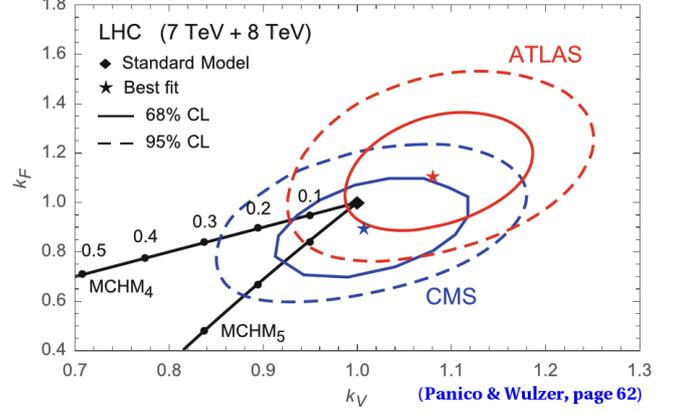
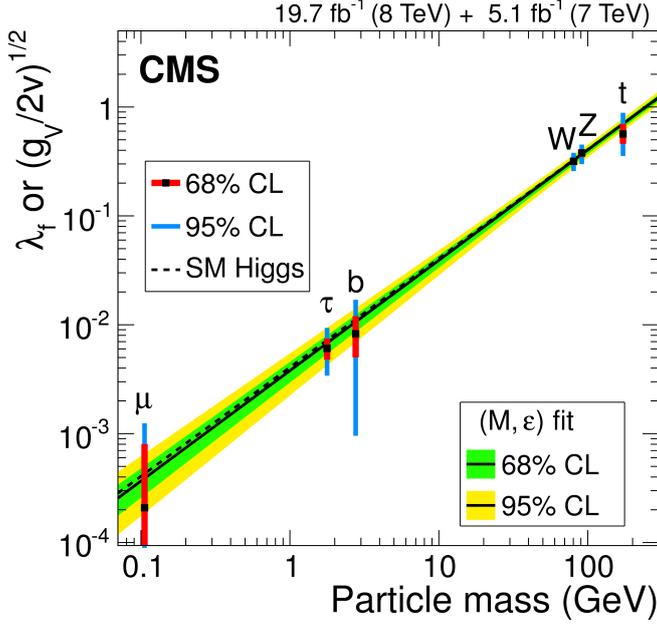
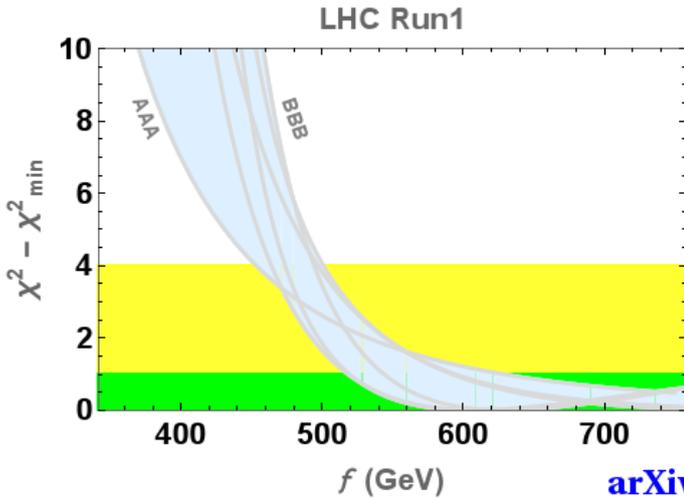


Figure 8: **Left:** Higgs couplings measured by CMS from Run I LHC data, currently highlighted among their [public results](#). **Right:** Run I constraints on Higgs couplings to the  $W$  and  $Z$  ( $\kappa_V$ ) and to the top quark ( $\kappa_F$ ), normalized to the standard model values and compared with MCHM predictions for a range of  $0 \leq \xi \leq 0.5$ . For non-zero  $\xi$  composite Higgs models universally predict  $\kappa_V, \kappa_F < 1$  at leading order.



[arXiv:1703.10190](#)

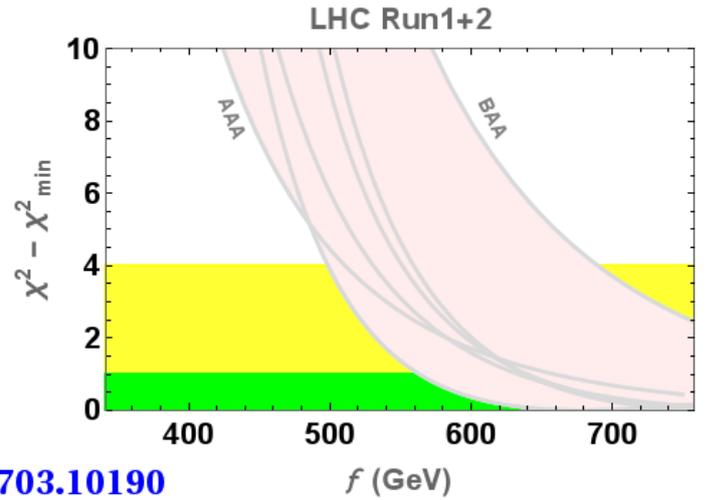


Figure 9: Relative quality of fits to ATLAS and CMS data as functions of  $f$  for composite Higgs models with either  $\kappa_F^A$  or  $\kappa_F^B$  (cf. Eq. 1) for the  $\{t, b, \tau\}$ , from [arXiv:1703.10190](#). Initial Run II data at  $\sqrt{s} = 13$  TeV increase the lower bound from  $f \gtrsim 450$  GeV to  $f \gtrsim 500$  GeV, with tighter constraints for certain cases.

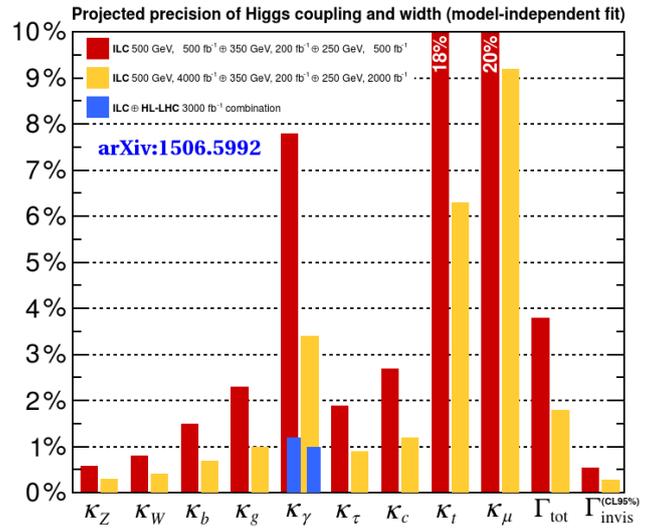
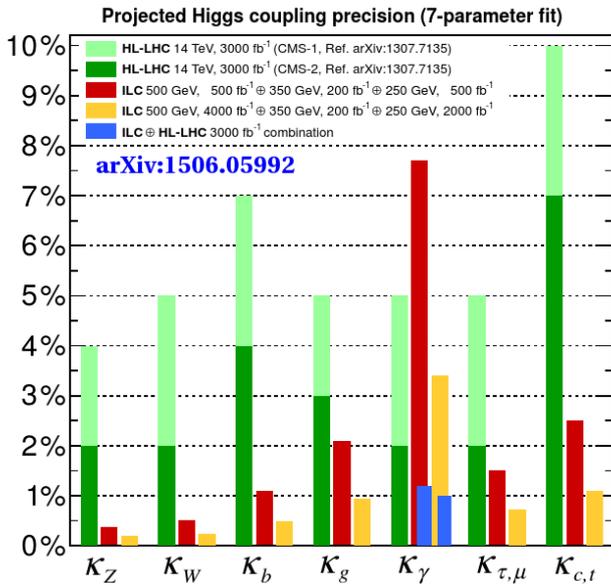


Figure 10: Expectations for the relative precision with which various Higgs couplings can be measured at the high-luminosity LHC and at a future  $e^+e^-$  International Linear Collider with  $\sqrt{s} = 500$  GeV, from [arXiv:1506.05992](https://arxiv.org/abs/1506.05992). The left (right) plots consider model-dependent (model-independent) analyses. The much greater precision with which most couplings can be determined at a future Higgs factory is a major motivation for constructing such a collider.

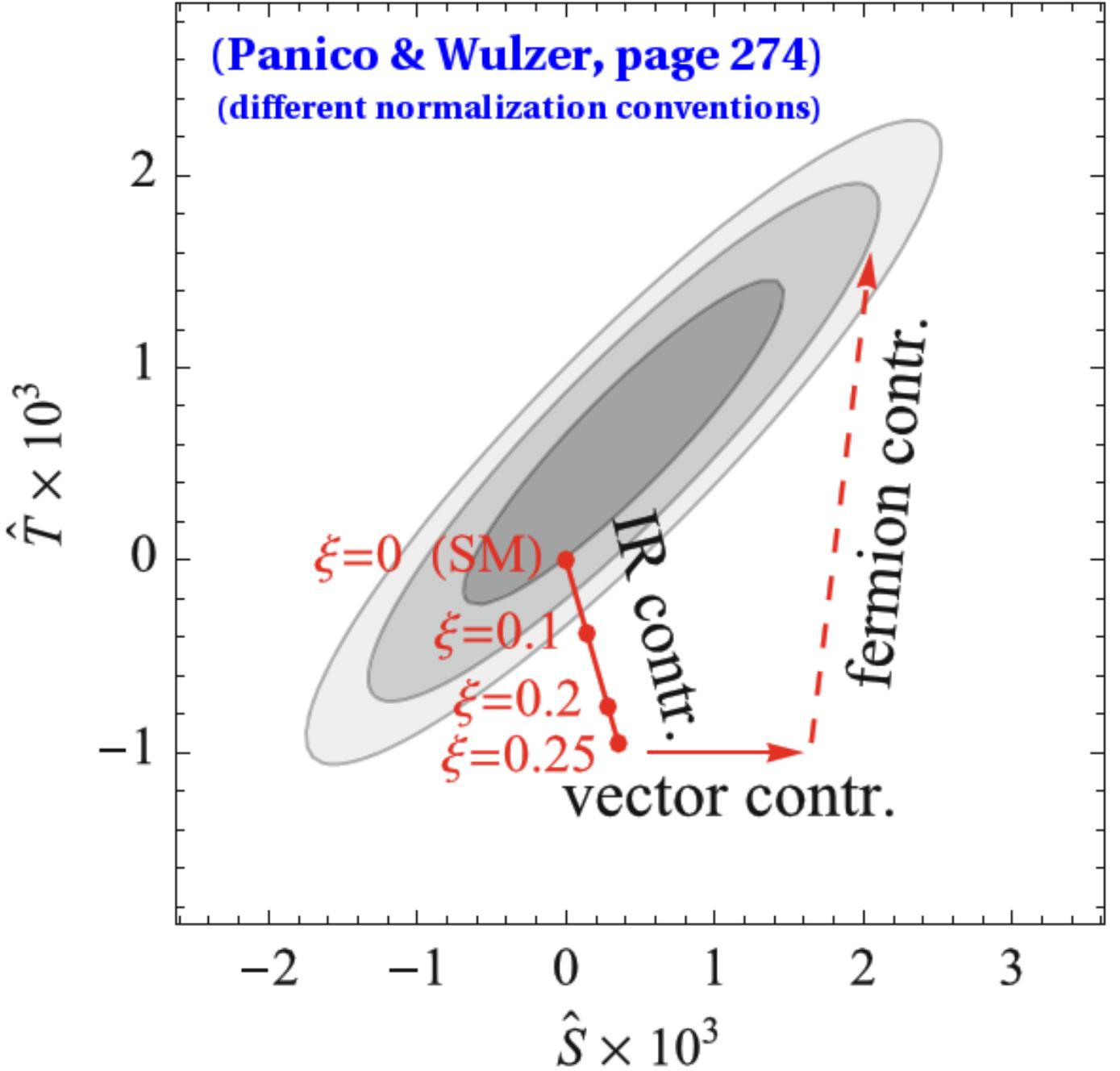


Figure 11: Three generic contributions to the electroweak precision parameters  $\hat{S} = \frac{\alpha_2}{4}S$  and  $\hat{T} = \alpha_{em}T$  from composite Higgs models. The IR contributions  $\propto \xi$  come from modified Higgs couplings (and potentially extra EW-charged PNGBs), the vector contribution to  $S$  comes from the usual  $\Pi'_{V-A}$ , and the fermion contributions (also  $\propto \xi$ ) come from loops involving composite top partners. All three contributions are positive for  $S$  while the IR contribution to  $T$  is negative and the vector contribution to  $T$  is negligible. The fermion contribution to  $T$  may have the positive sign needed to cancel the IR contribution and recover agreement with the experimental bounds shown by the ellipses.