New strong dynamics beyond the standard model

Lecture 4 21 November 2017

Last time

- Partial compositeness results from linear mixing ($\sim \lambda_q \overline{q} \mathcal{O}_q$)
  between elementary fermions q and composite partners $\mathcal{O}_q$
- Partial compositeness can provide viable EWSB potential for PNGB Higgs,
  with both non-zero vev $\langle h \rangle \neq 0$ and $\xi = \frac{v^2}{f^2} = \sin^2\left(\langle h \rangle / f\right) \ll 1$
- 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 $\mathcal{G} \to \mathcal{H}$ symmetry breaking
- 'Minimal' UV completions have $\mathcal{G} = \mathrm{SU}(F)$ or $\mathrm{SU}(F) \times \mathrm{SU}(F)$
  (no obvious UV completion for holography-based SO(5)/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 $\xi = \frac{v^2}{f^2} = \sin^2\left(\langle h \rangle / f\right)$
  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 PNGBs; top partners
- Heavy vector like the ρ of QCD present even for minimal models, with $M_V \simeq 4\pi f$
  Expect decays mostly to 2 (P)NGBs (i.e., $V_L V_L$, $V_L H$), smaller rates to SM $\psi\overline{\psi}$
- Extra PNGBs 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 $\longrightarrow$ colored top partners with $M_T \ll 4\pi f$
- Higgs couplings $\longrightarrow$ 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–$\overline{D}$ mixing, CP violation)

Direct searches for heavy vectors and PNGBs

- Many models and many searches $\longrightarrow$ 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
- $\longrightarrow$ Increasing $\sqrt{s}$ can have big effects on production cross sections
- Diboson constraints reach ∼3 TeV, for $\sqrt{s} = 8$ & 13 TeV (as of ICHEP2016)
  Using NDA expectation $M_V \simeq 4\pi f \longrightarrow f \gtrsim 240$ GeV gives no constraint,
  but scaling up QCD $M_\rho/f \simeq 8$ suggests $f \gtrsim 375$ GeV $\longrightarrow \xi \lesssim 0.43$
- If non-minimal PNGBs π^a with $M_P \ll 4\pi f$ can decay to dibosons,
  then constraints are more significant: $f_\chi \gtrsim 500$ GeV $\longrightarrow \xi \lesssim 0.24$ for color octets
- PNGBs decay to dibosons through WZW terms $\sim c^{abc}\pi^a\epsilon^{\mu\nu\alpha\beta}A^b_{\mu\nu}A^c_{\alpha\beta}$
  $\longrightarrow$ 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 Γ/M) among other conditions
  This is problematic for QCD-like $\Gamma_\rho/M_\rho \approx 150/770 \approx 0.19$,
  and larger Γ/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$_5$ analyses $\longrightarrow f \gtrsim 600$ GeV ($\xi \lesssim 0.17$) to produce correct Higgs mass
- Experimental results include searches for exotically charged $X_{5/3} \to W^+ t$

Higgs couplings

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

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

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

  ($\text{MCHM}_4 \longrightarrow A$; MCHM_5, NMCHM, Georgi–Kaplan coset $\longrightarrow B$)

- $\kappa_F \lesssim 1$ 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 τ measured to be within $\mathcal{O}(10\%)$ of SM values
  For $\text{MCHM}_{4/5}$ find $\xi < 0.2 \longrightarrow f = v/\sqrt{\xi} \gtrsim 550$ GeV from LHC Run I
- Can also define κ_g and κ_γ for effective hgg and $h\gamma\gamma$ couplings
  If only one dominant top partner, its effects cancel in κ_g $\quad$ [$\kappa_g = \left(\kappa_F^B\right)^2$ in MCHM_5]
  (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, $\propto \xi \log\left(\frac{\Lambda^2}{M_H^2}\right)$, $\quad \Lambda = 4\pi f$ or M_V
- Extra PNGBs in non-minimal models can also add similar chiral logs,
  depending on how they transform under $\text{SU}(2)_L \times \text{U}(1)_Y$
- 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,

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

- In the large-N limit, can approximate $R(s)$ as sum of narrow poles
  Keeping only first pole in each channel, $R(s) \to 12\pi^2 F^2 \delta(s - M^2)$,
  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 $Q^2 \to \infty$)

$$\int ds\left[R_V(s) - R_A(s)\right] = 12\pi^2 F_P^2 \qquad\qquad \int ds\ s\left[R_V(s) - R_A(s)\right] = 0$$

$$\longrightarrow F_V^2 - F_A^2 = F_P^2 > 0 \qquad\qquad F_V^2 M_V^2 - F_A^2 M_A^2 = 0$$

- 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:

$$|\text{Re}\left[C_K\right]| \lesssim 9.6 \times 10^{-13}\ \text{GeV}^{-2} \qquad |C_D| \lesssim 7.2 \times 10^{-13}\ \text{GeV}^{-2}$$

$$|C_B| \lesssim 2.3 \times 10^{-11}\ \text{GeV}^{-2} \qquad |C_{B_s}| \lesssim 1.1 \times 10^{-9}\ \text{GeV}^{-2}$$

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

- For bilinear case $C \sim 1/\Lambda_F^2$, these lead to $\Lambda_F^{(c)} \gtrsim 1500$ TeV from D–$\overline{D}$ mixing
  and $\Lambda_F^{(s)} \gtrsim 10{,}000$ TeV from CP violation in strange sector

- Although partial compositeness allows a high flavor scale $\Lambda_F \gtrsim 10^{13}$ 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 $4\pi f \gtrsim 10$ TeV
  $\longrightarrow f \gtrsim 800$ GeV or $\xi \lesssim 0.1$ comparable to constraints from Higgs couplings

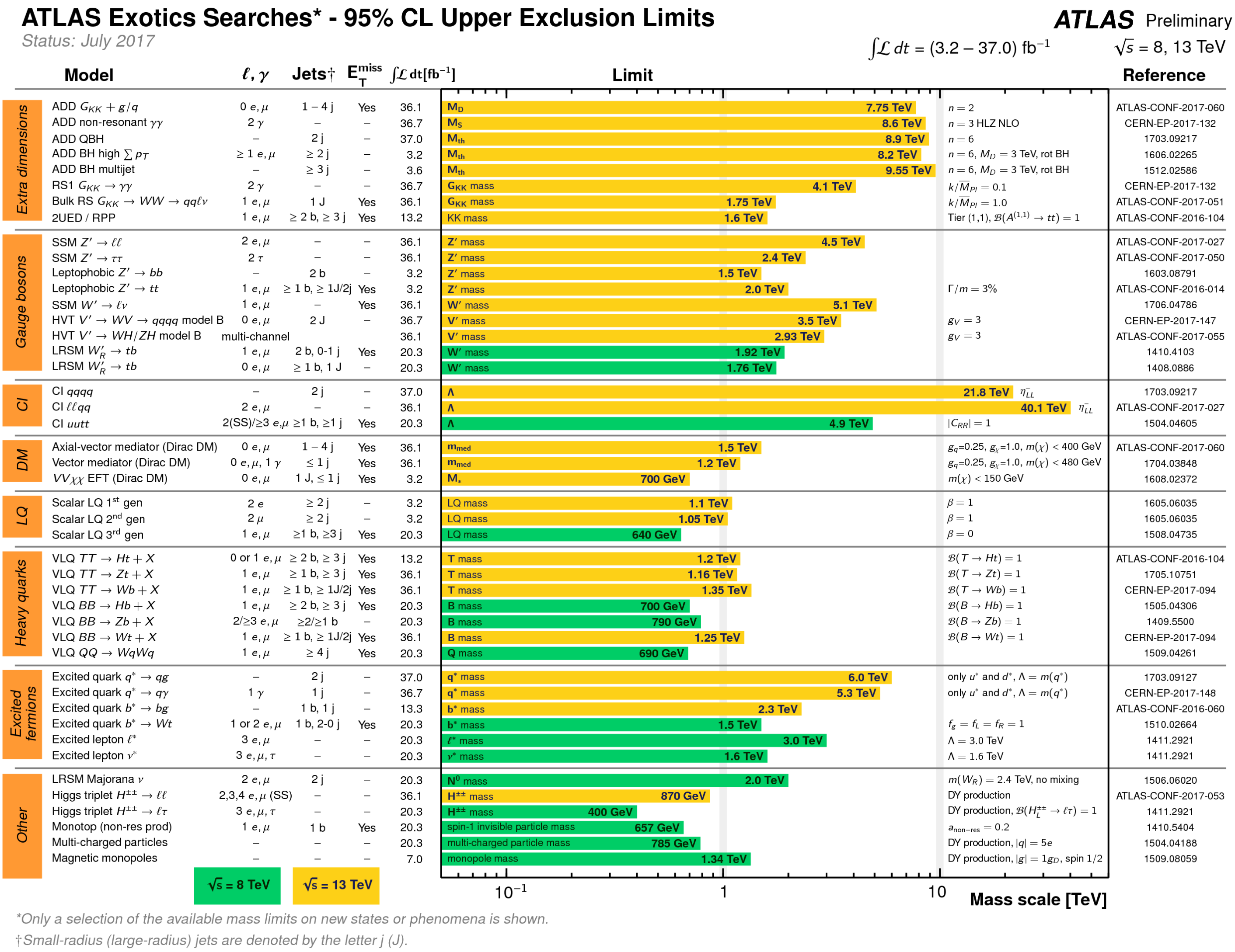

Figure 1: Summary of mid-2017 constraints from searches for relatively generic ‘exotic’ particles by ATLAS. Constraints that may be relevant to composite Higgs models include the heavy vector triplet (HVT) bound $M_V \gtrsim 3$ TeV, vector-like quark (VLQ) bounds $M_T \gtrsim 1$ TeV, and Higgs triplet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

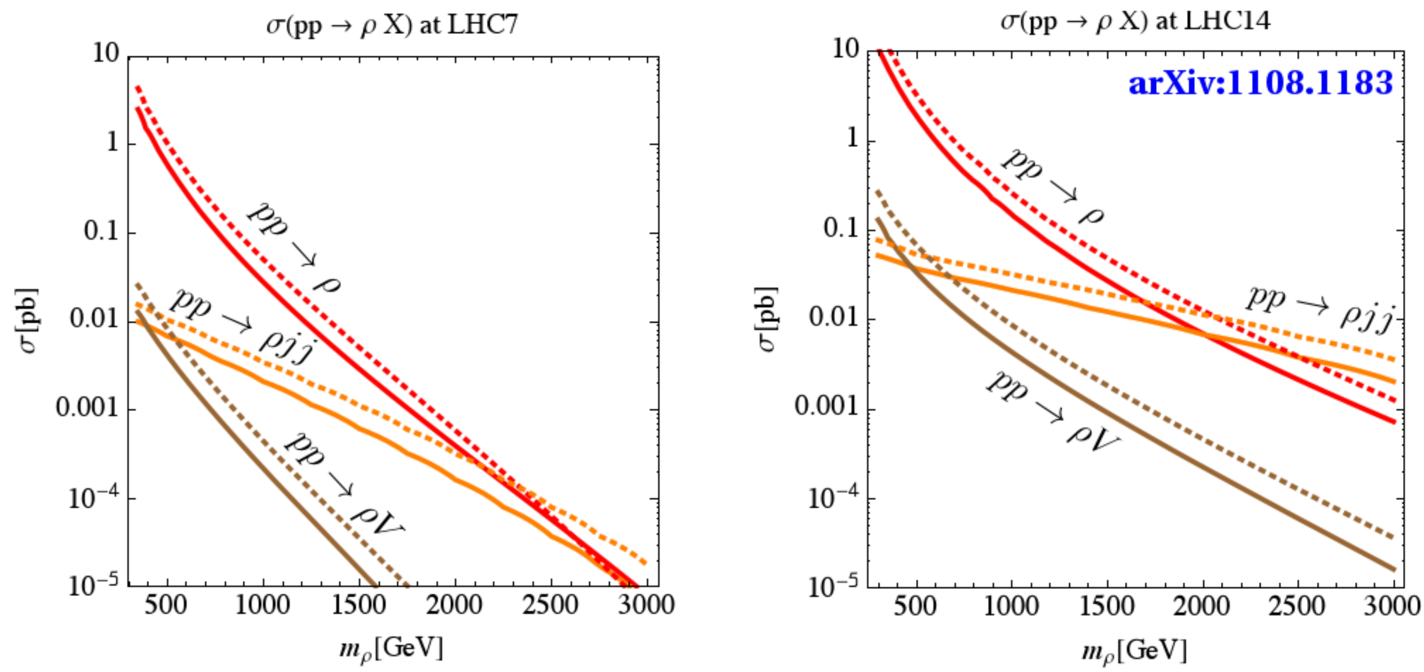

Figure 2: LHC production cross sections for a single charged (dotted) or neutral (solid) heavy vector boson 'ρ', in the Drell–Yan (red), vector-boson-fusion (orange) and ρ-strahlung (brown) channels, from arXiv:1108.1183. The larger $\sqrt{s} = 14$ TeV (right) significantly enhances the cross sections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

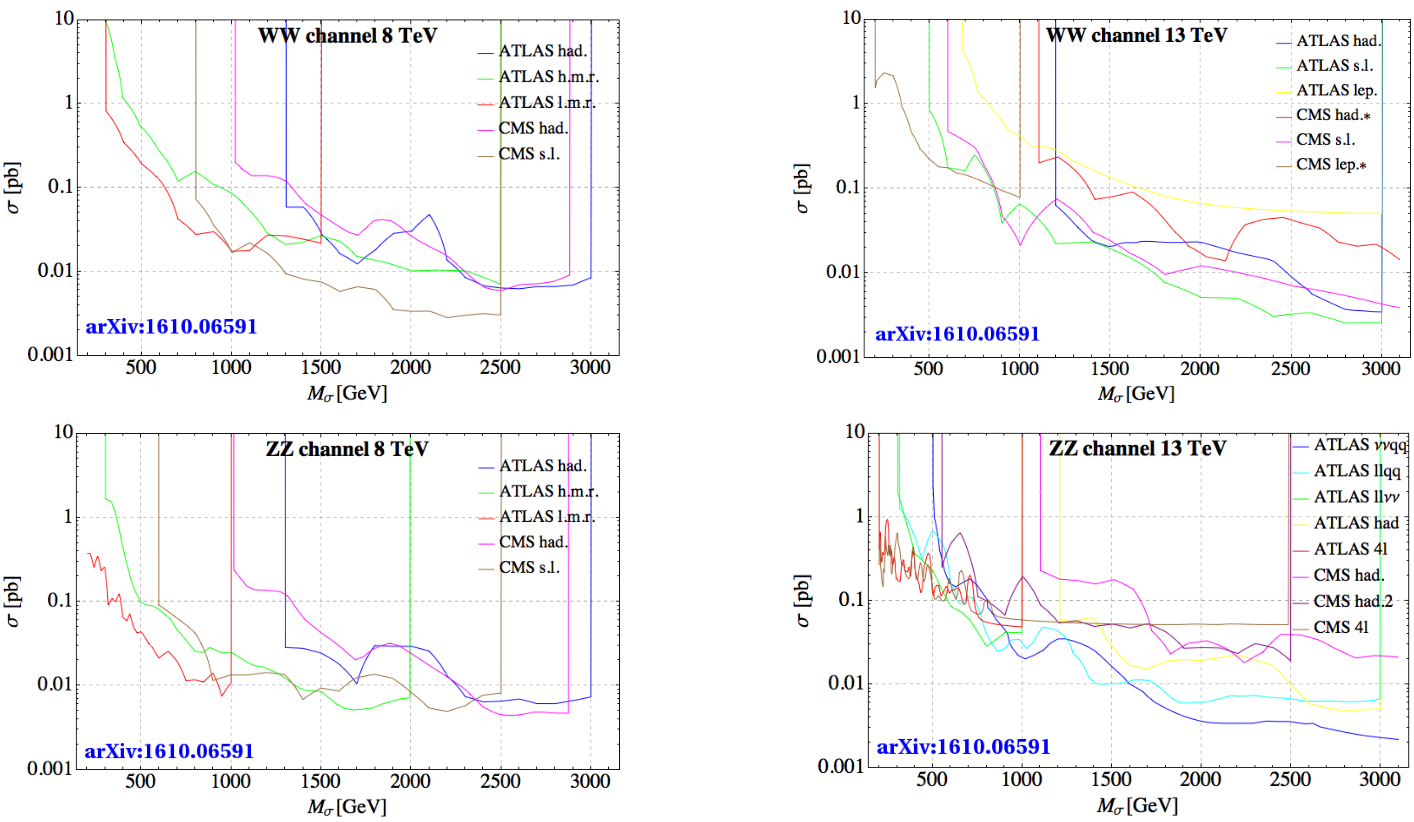

Figure 3: LHC bounds on cross section × branching fraction for WW (top) and ZZ (bottom) final states, from multiple 8 TeV (left) and 13 TeV (right) LHC searches, collected in arXiv:1610.06591.

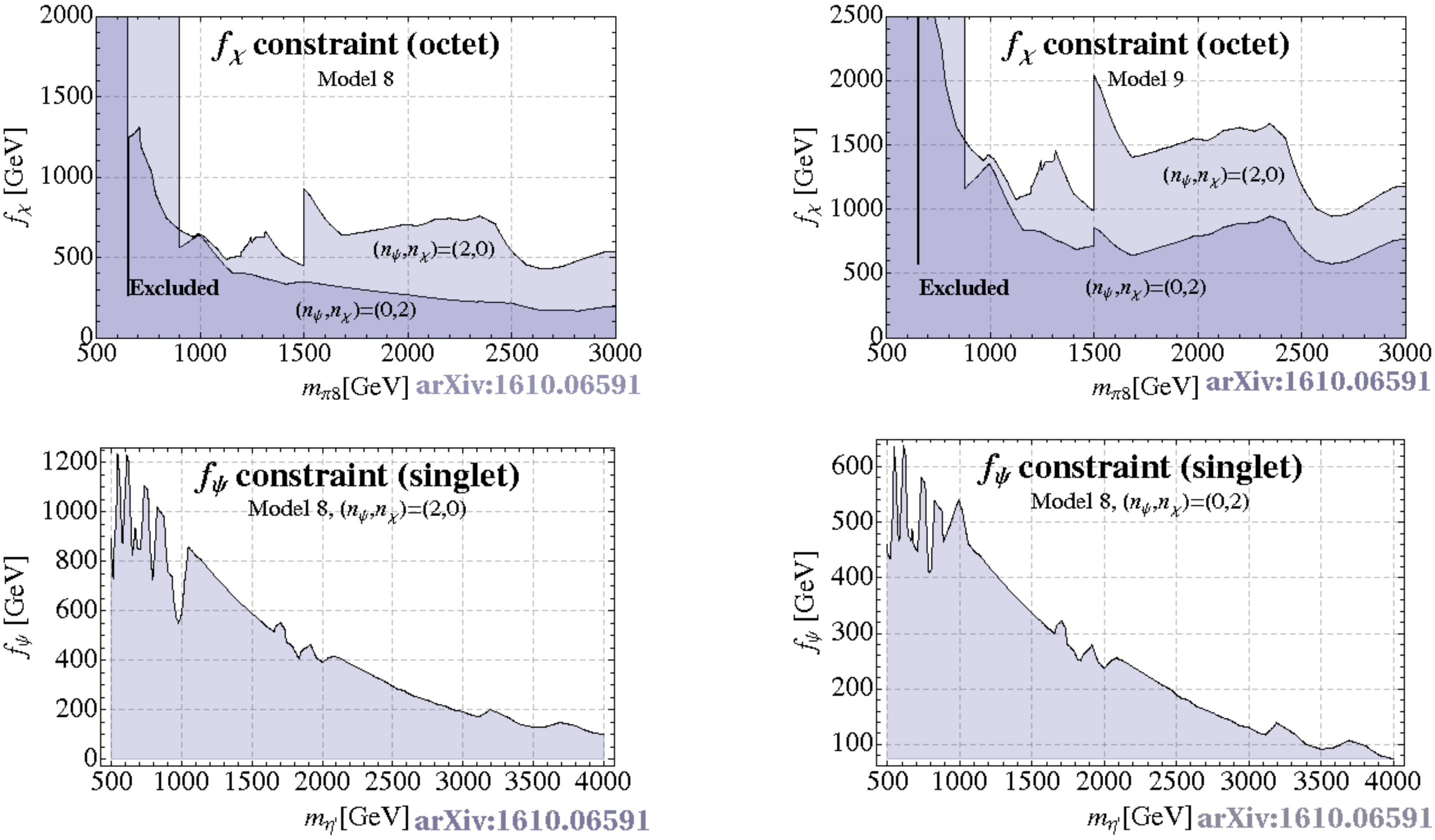

Figure 4: Constraints from arXiv:1610.06591 on the two symmetry breaking scales f in two non-minimal composite Higgs models based on multi-rep partially composite UV completions, using the diboson bounds in the previous figure along with other LHC data. The χ fermions carry QCD color while the ψ fermions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

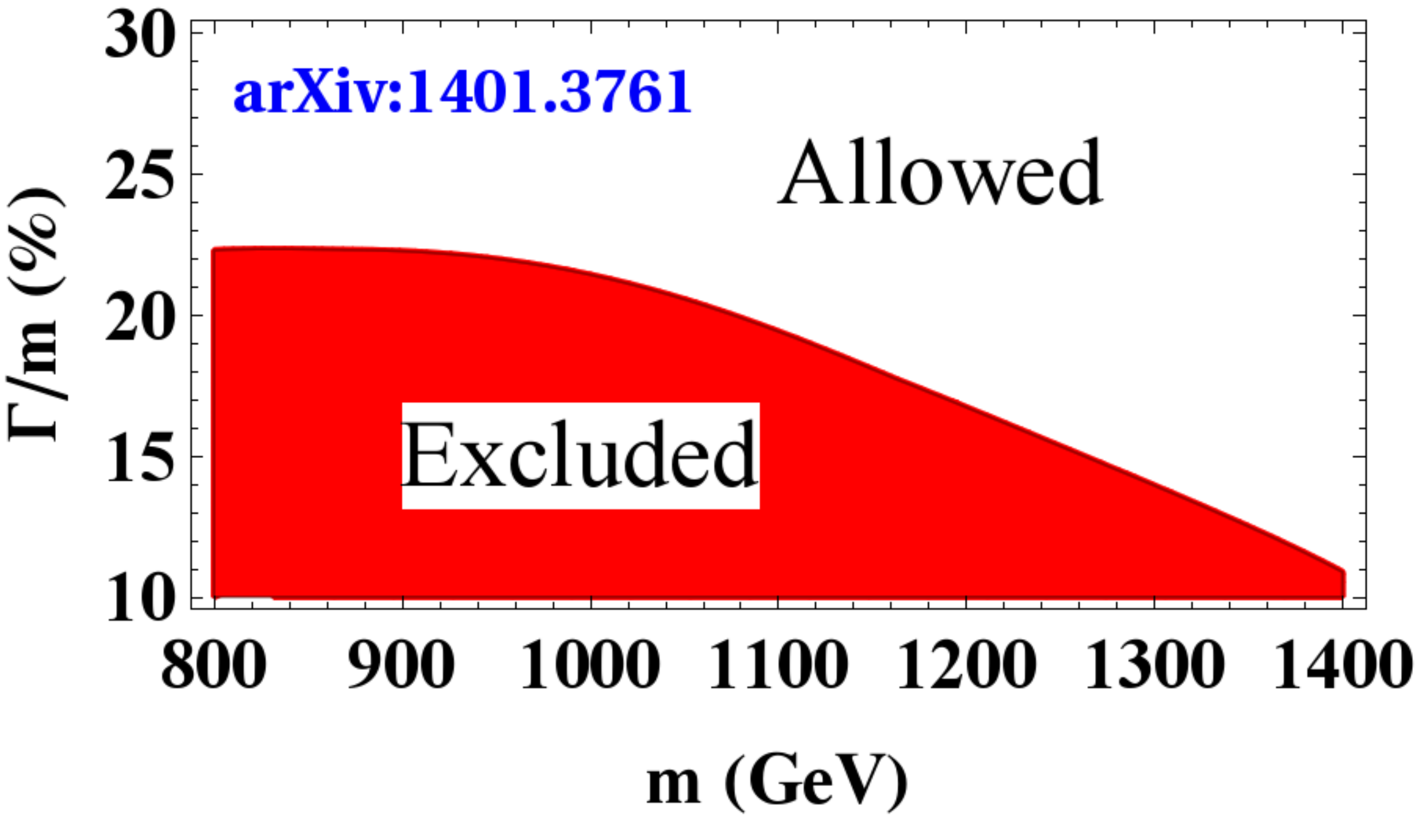

Figure 5: Illustration of how LHC constraints on heavy vectors become weaker as the width Γ of the new resonance increases compared to its mass m, from arXiv:1401.3761. The data being considered come from CMS-PAS-EXO-12-025, a search for $W' \to WZ \to$ leptons based on 19.6/fb of $\sqrt{s} = 8$ TeV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

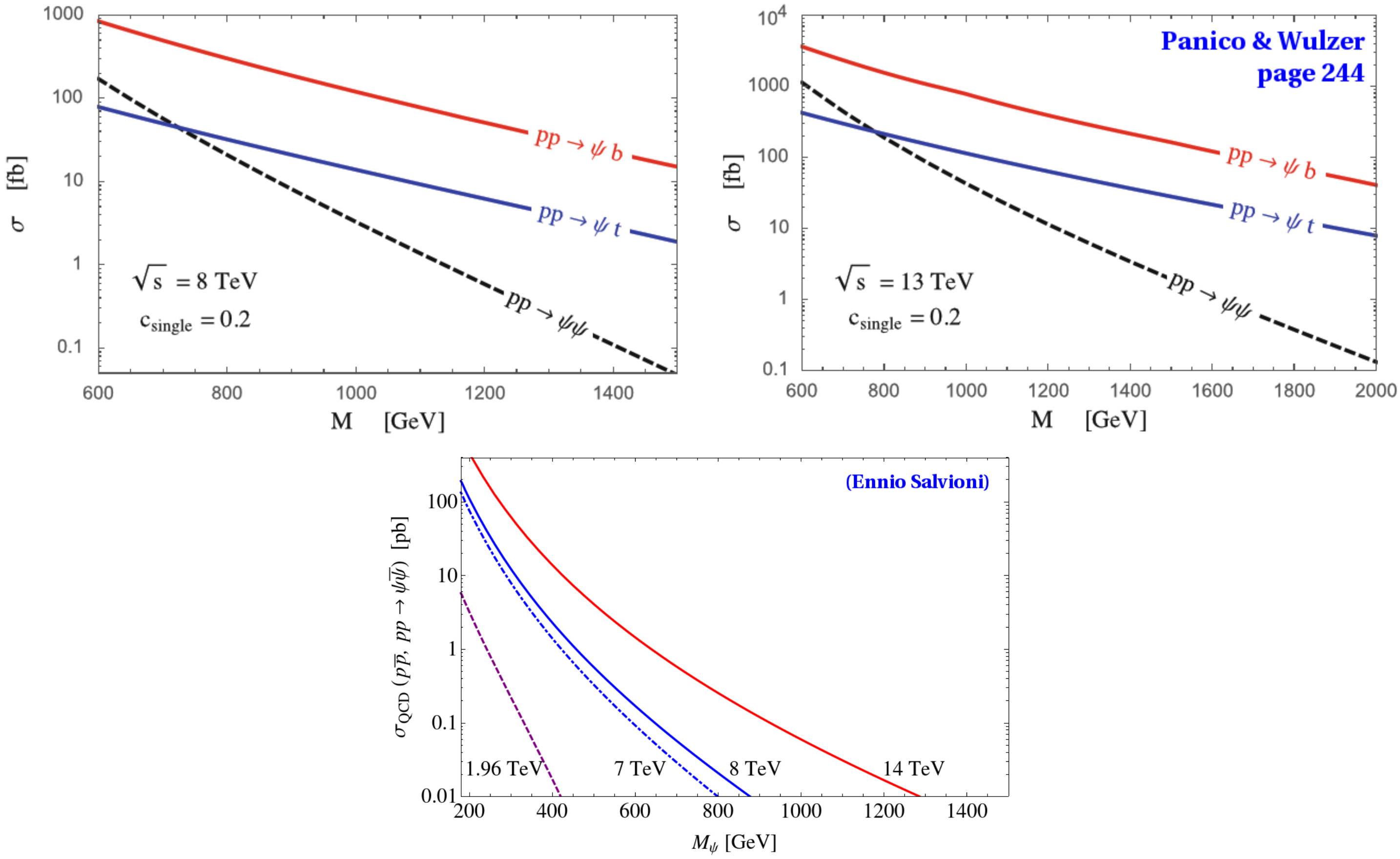

Figure 6: **Top:** LHC production cross sections for either one or two top partners ψ, with $c_{\text{single}} = g_2\sqrt{\xi} \approx 0.65\sqrt{\xi}$. For $M_\psi \gtrsim 750$ GeV the larger top partner mass leads the pair-production cross section to fall below the single-production cross section. **Bottom:**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

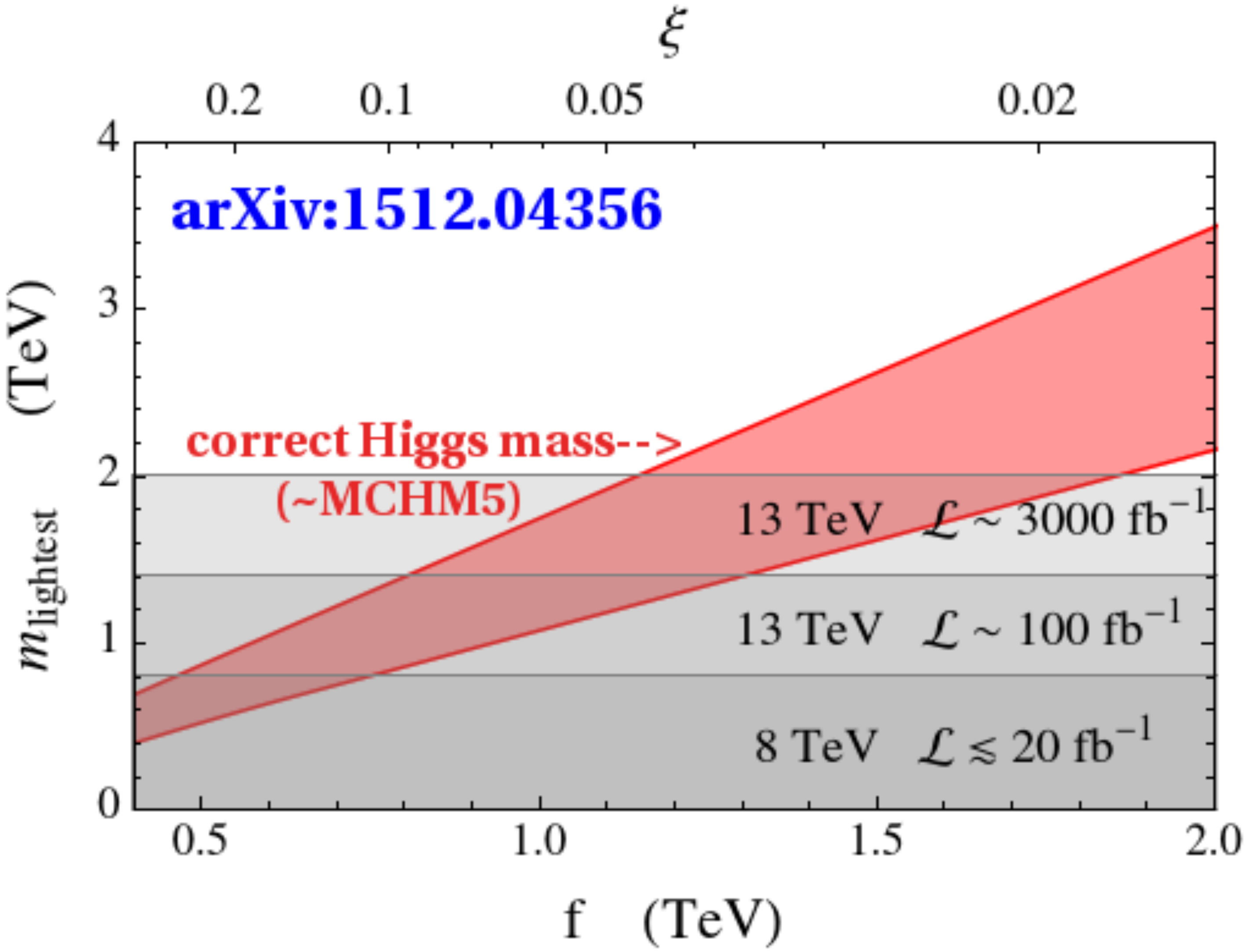

Figure 7: Current and projected LHC constraints on the lightest top partner mass in the MCHM_5 (typically an exotically charged $X_{5/3}$), from arXiv:1512.04356. The red band estimates (with $\sim$20% precision to account for approximations in the analyses) the corresponding symmetry breaking scale f that should produce the correct Higgs mass in this model.

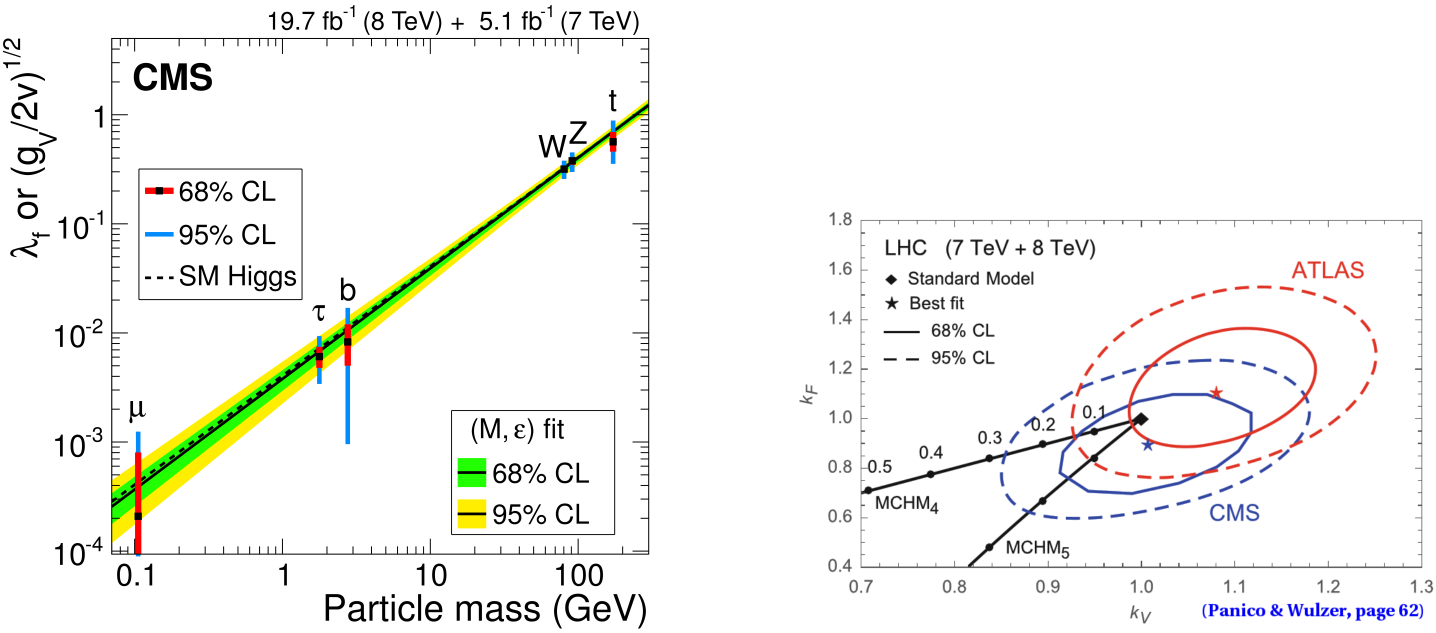

Figure 8: **Left:** Higgs couplings measured by CMS from Run I LHC data, currently highlighted among their public results. **Right:** Run I constraints on Higgs couplings to the W and Z (κ_V) and to the top quark (κ_F), normalized to the standard model values and compared with MCHM predictions for a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

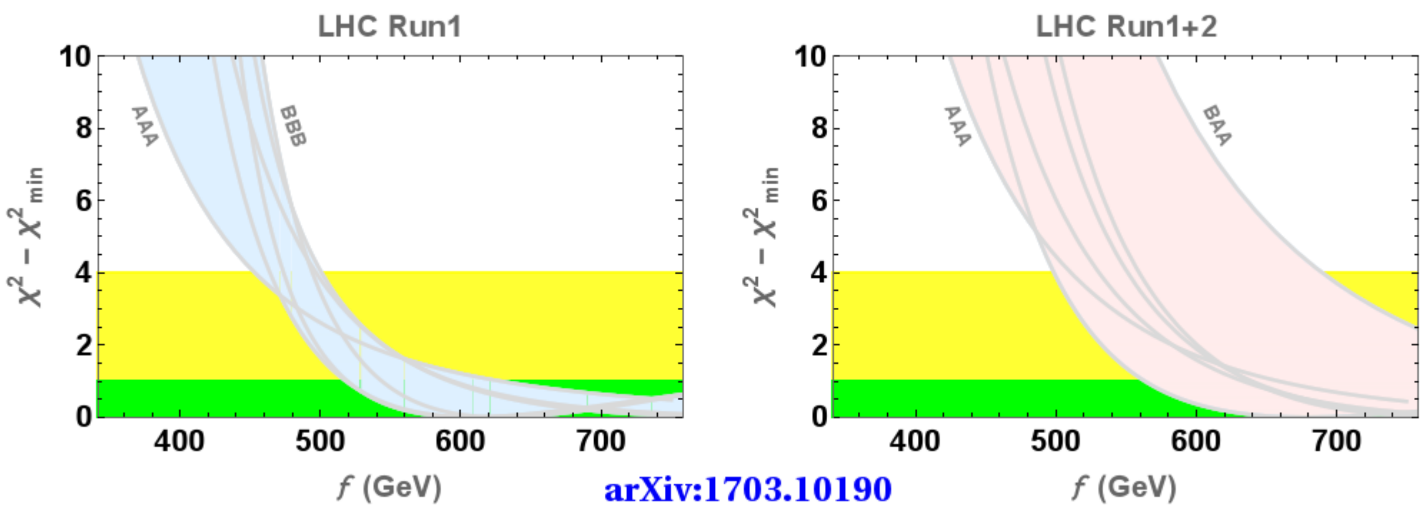

Figure 9: Relative quality of fits to ATLAS and CMS data as functions of f for composite Higgs models with either κ_F^A or κ_F^B (cf. Eq. 1) for the $\{t, b, \tau\}$, from arXiv:1703.10190. Initial Run II data at $\sqrt{s} = 13$ TeV increase the lower bound from $f \gtrsim 450$ GeV to $f \gtrsim 500$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

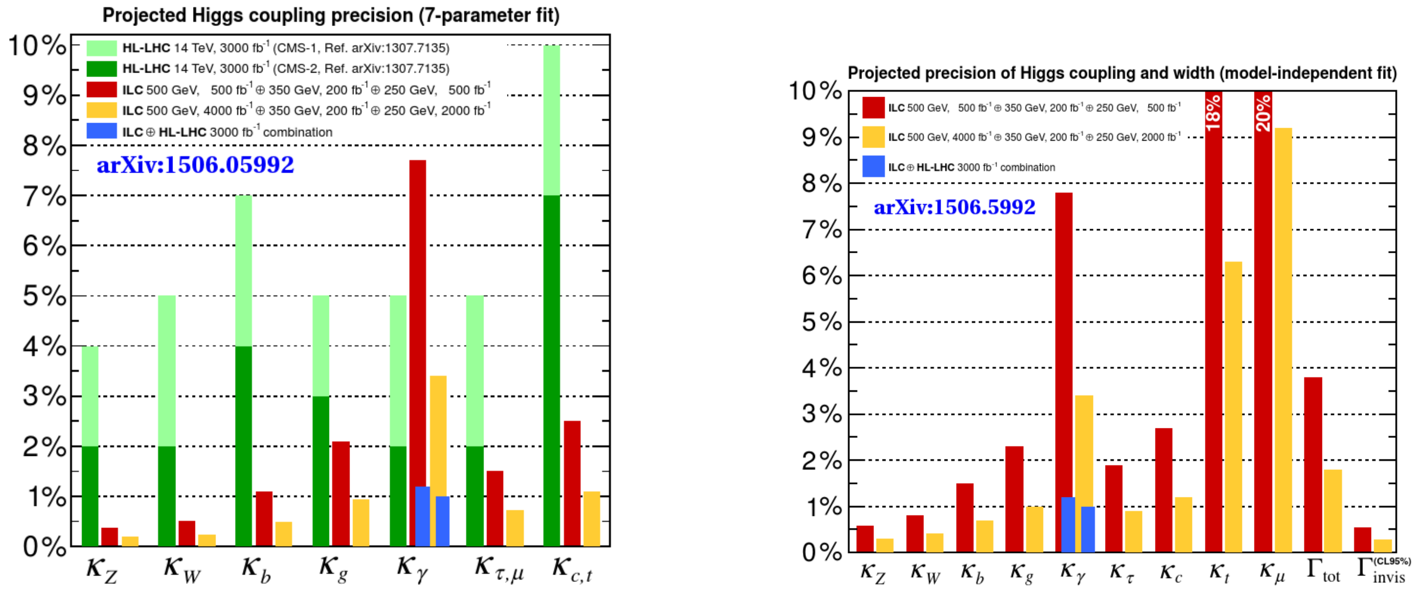

Figure 10: Expectations for the relative precision with which various Higgs couplings can be measured at the high-luminosity LHC and at a future e^+e^- International Linear Collider with $\sqrt{s} = 500$ GeV, from arXiv:1506.05992. The left (right) plots consider model-dependent (model-independent) analyses. 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.

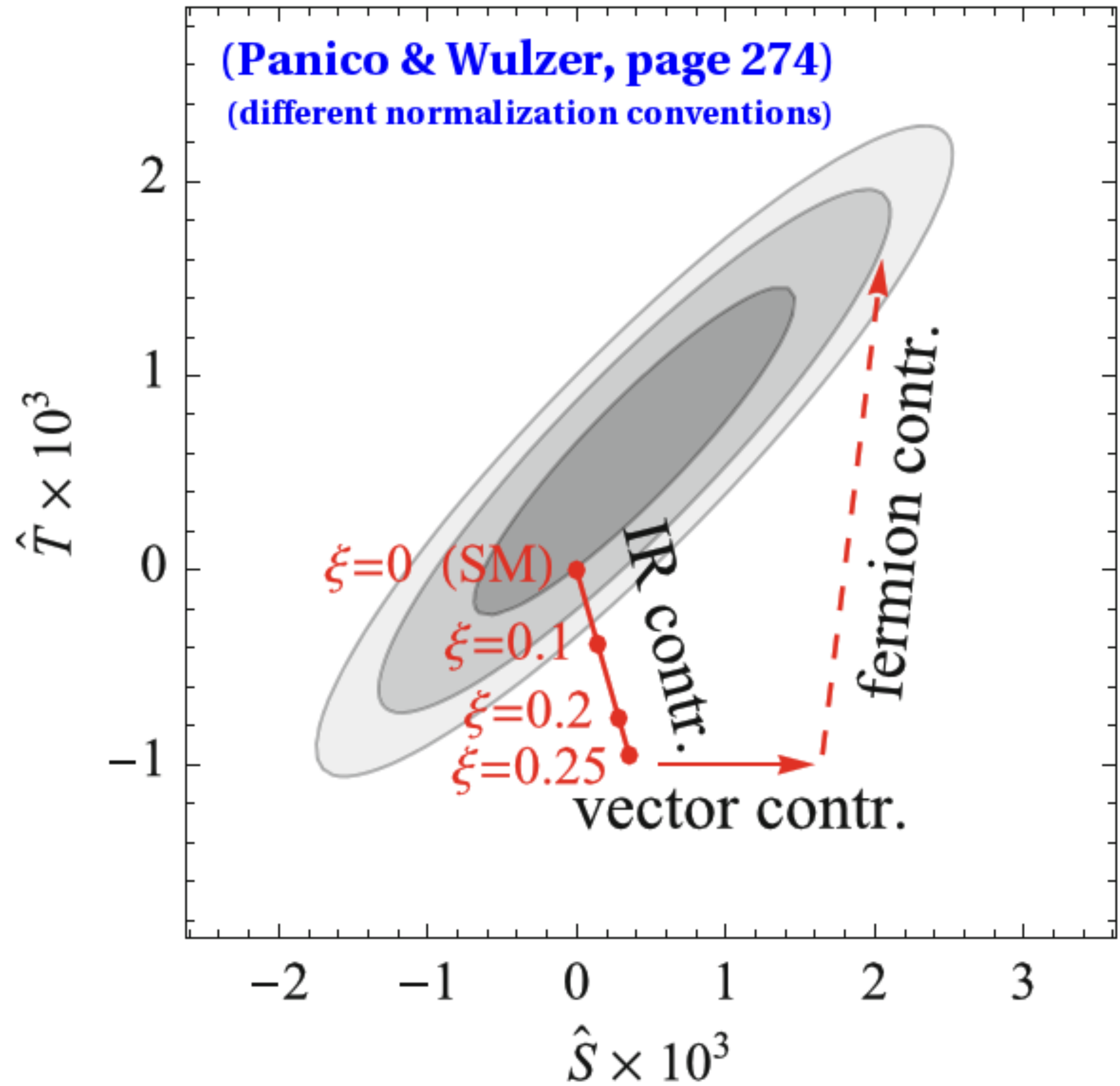

Figure 11: Three generic contributions to the electroweak precision parameters $\widehat{S} = \frac{\alpha_2}{4} S$ and $\widehat{T} = \alpha_{em} T$ from composite Higgs models. The IR contributions $\propto \xi$ come from modified Higgs couplings (and potentially extra EW-charged PNGBs), the vector contribution to S comes from the usual Π'_{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.