The Higgs and vector resonances in bosonic technicolor

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especially Patipan for preparing most of the plots

Plan

- Introduction
- Higgs phenomenology
- S and T away from the chiral limit
- vector phenomenology

Introduction

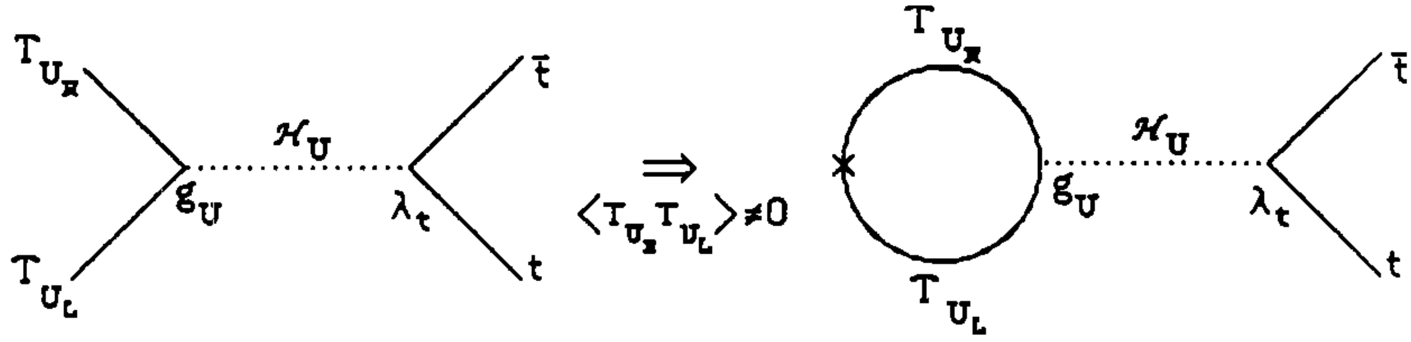
- BTC combines technicolor and supersymmetry Dine, A.K., Samuel, 1990; non-susy version: Simmons, 1989
- technicolor condensates trigger electroweak symmetry breaking
- fundamental Higgs fields H_u, H_d give masses to quarks, leptons
- supersymmetry stabilizes the Higgs scalar masses
- Higgs VEV's via Yukawa couplings to technifermion condensates

$$\lambda_U \bar{U}_R T_L H_u + \lambda_D \bar{D}_R T_L H_d \Rightarrow \langle H_u \rangle \sim \lambda_U \frac{\langle \bar{U}_R U_L \rangle}{m_{H_u}^2}, \quad \langle H_d \rangle \sim \lambda_D \frac{\langle \bar{D}_R D_L \rangle}{m_{H_d}^2}$$

  - positive Higgs mass parameters, $m_{H_u}^2, m_{H_d}^2 > 0 \Rightarrow$ no electroweak symmetry breaking in absence of TC

- W, Z receive masses both from technicolor condensates, HIggs VEV's

$$v_W^2 = (246\ \mathrm{GeV})^2 \approx f_{\mathrm{TC}}^2 + f_u^2 + f_d^2, \qquad \langle H_{u,d} \rangle \equiv f_{u,d}/\sqrt{2}$$



-Fermion mass generation in BTC via “Higgs scalar exchange", integrated out in heavy limit

-for light Higgs, use chiral Lagrangian approach Carone, Simmons; Carone, Georgi

- Minimal BTC = MSSM + $SU(N)_{\rm TC}$, with technifermion superfields

$$\hat{T}_L(2_{\rm TC}, 1_C, 2_L, 0), \quad \hat{U}_R(2_{\rm TC}, 1_C, 1_L, -1/2), \quad \hat{D}_R(2_{\rm TC}, 1_C, 1_L, +1/2),$$

  and Yukawa superpotential

$$W_{\rm Y} = \lambda_U \hat{U}_R \hat{T}_L \hat{H}_u + \lambda_D \hat{D}_R \hat{T}_L \hat{H}_d$$

  - $N_{\rm TC} = 2$ is minimal choice
  - $N_{\rm TC} = 3$ disfavored: stable fractionally charged technibaryons; $SU(2)_L$ anomaly
  - $N_{\rm TC} = 4$ disfavored by S parameter

- superpartner technigluino, technisquarks acquire masses $> \Lambda_{\rm TC}$, yielding a QCD-like technicolor theory at lower scales

Original Motivation - 90's

- large m_h easily obtained: unlike MSSM, where $m_h \sim m_Z$, in BTC m_h not tied to quartic coupling - little change if set D^2 terms to zero
- at the time, $m_t \gtrsim 100$ GeV
- for $\lambda_U \sim 1$ and top Yukawa $y_t \sim 1$, was possible to obtain $m_t \sim 100$ GeV for $m_h \sim 1/2$ TeV
  - $\Rightarrow$ multi-TeV squark, slepton masses (5-10 TeV) natural
- motivation was to combine SUSY and TC, to ease FCNC problems in each
  - heavy superpartners $\Rightarrow$ SUSY FCNC problem alleviated - relaxed degeneracy
  - Extended TC fermion mass generation plagued by FCNC problems, unlike Higgs Yukawa couplings

As it turned out

- top significantly heavier, Higgs significantly lighter (preferred by precision electroweak for some time)

- combined with preference for perturbative $O(1)$ top and TC Yukawa couplings, to allow $m^2_{H_u}, m^2_{H_d} > 0$ without fine-tuning

$$\Rightarrow \quad v_W^2 \approx f_u^2 + f_d^2 \gg f_{\rm TC}^2, \quad \text{e.g. } f_{\rm TC} \lesssim 100 \text{ GeV}$$

  - bulk of W, Z masses come from Higgs VEV's, but EWK symmetry breaking triggered by TC: $f_{\rm TC} \neq 0$ AK, KITP '08; Azatov, Galloway, Luty '11

  - $f^2 << v_W^2$, light Higgs also considered in non-susy BTC
Carone, Simmons; Carone, Georgi; Antola et al.

- light Higgs $\Rightarrow$ relaxing SUSY FCNC no longer a motivation
- However, from low energy perspective, $m_h \approx 125$ GeV is easy: no fine-tuned cancelations in scalar potential, no need for heavy stops with large left-right mixing,...
- as in MSSM, Higgs mass parameters log sensitive to large SUSY breaking mediation scales
  - perhaps $U(1)_R$ symmetric BTC with Dirac $SU(3)_C$ and TC gauginos, i.e. with supersoft properties, can improve the situation (under investigation)
  - add TC adjoint and $\mathrm{SU}(3)_\mathrm{c}$ adjoint matter superfields a_{TC}, a_C to minimal BTC set-up $\Rightarrow$ $m_{\tilde{g}_{\mathrm{TC}}}\, \tilde{g}_{\mathrm{TC}}\, a_{\mathrm{TC}}, \;\; m_{\tilde{g}}\, \tilde{g}\, a_\mathrm{C}$
  - advantage over R-symmetric MSSM (and MSSM in general)
    - μ problem may be solved via partial compositeness: higgsinos, electroweak gauginos gain mass via mixing with technifermion-techniscalar bound states,

$$\text{e.g.} \quad \lambda_U\, \tilde{h} T_L \tilde{U}_R \rightarrow m\, \tilde{h}\, \psi_1, \quad g_2\, \tilde{w}\, T_L \tilde{T}_L \rightarrow m'\, \tilde{w}\, \psi_2$$

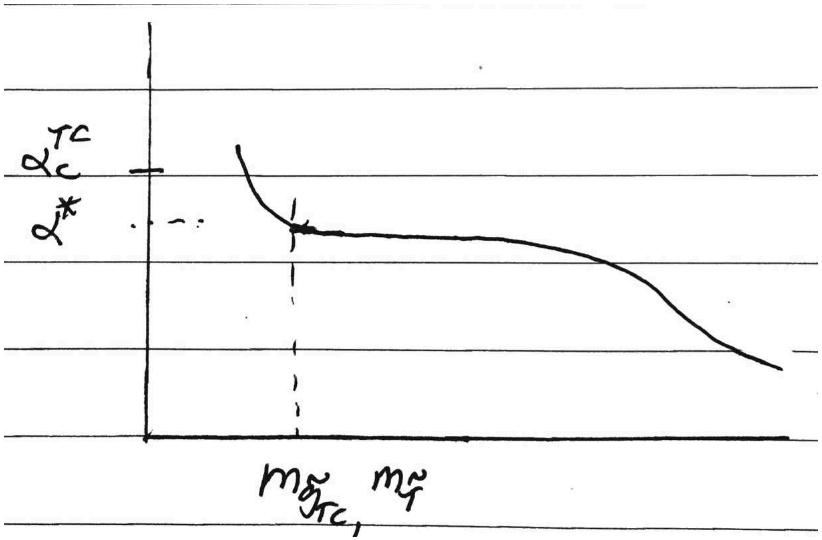
Linking $\Lambda_{\rm TC}$ and $m_{\rm susy}$

- BTC introduces two scales at low energies: (i) m_{susy}, the scale of superpartner masses; (ii) $\Lambda_{\rm TC}$, the scale of TC chiral symmetry breaking
- potential coincidence problem since, e.g. $m_{\rm susy}/\Lambda_{\rm TC} = O(\text{few})$
- when techni-superpartners acquire masses and “decouple", technicolor beta function becomes more negative.
  - more rapid increase in $\alpha_{\rm TC}$ below $m_{\rm susy}$ could link the two scales
    AK, Samuel ’91

- most attractive scenario Azatov, Galloway, Luty '11:
  above $m_{\rm susy}$, $\alpha_{\rm TC}$ sits near a superconformal strong IR fixed point. Provides direct link between $m_{\rm susy}$ and $\Lambda_{\rm TC}$

- appealing realization: susy $SU(2)$ with $n_f = 2$ and one adjoint matter superfield is known to have a strongly interacting IR fixed point
  Elitzur, Forge, Giveon, Rabinovici '95

  - R symmetric BTC has precisely this TC field content. Can yield the following running of $\alpha_{\rm TC}$:



Higgs Phenomenology

- in chiral limit $\lambda_{u,d} \to 0$, $M_{R,L} \to 0$: TC sector has global $SU(4)$ symmetry
- Yukawa couplings ensure desired vacuum alignment
  $\langle \bar{U}_R T_L \rangle, \langle \bar{D}_R T_L \rangle \neq 0 \Rightarrow \mathrm{SU}(4) \to \mathrm{Sp}(4) \Rightarrow$ 5 pseudo-NGB's
- π^a : the usual $SU(2)_L \times SU(2)_R \to SU(2)_V$ triplet
- π_{UD}, $\pi_{\bar{U}\bar{D}}$: “baryonic" states which could lead to TC dark matter candidate
  Ryttov, Sanino; Frandsden, Sanino

for Higgs phenomenology suffices to consider $SU(2)_L \times SU(2)_R$ subgroup of $SU(4)$:

- taking into account MSSM scalar fields, after electroweak symmetry breaking have 8 physical linear combinations of MSSM scalars and TC pions, σ
  - one light higgs h, two heavy Higgs H
  - two charged pions $\pi_1^\pm$, $\pi_2^\pm$
  - two neutral pions π_1^0, π_2^0
- recently, have included a heavy scalar $\sigma[\bar{T}T]$ bound state with $\langle\sigma\rangle = f$
  - in QCD the σ has $O(1)$ width, due to $\sigma \to \pi\pi$
  - over the years this has led to a bias against consideration of a σ in TC
  - but BTC is far from the chiral limit. The π are heavy $\Rightarrow$ $\sigma \to \pi\pi$ channel is closed, or suppressed, leading to a relatively narrow σ

$$\Gamma_\sigma / m_\sigma \leq O(10\%), \mathrm{due\ to}\ \sigma \to (W,Z)\pi, WW, ZZ$$

TC Chiral Lagrangian

Employ two flavor $SU(2)_L \times SU(2)_R$ non-linear sigma model chiral Lagrangian $\mathcal{L}_\chi$+ MSSM Higgs scalar potential

$$\text{Yukawa couplings} : -\bar{T}_L\,\Phi_\Lambda\,T_R + h.c., \quad T_{R\,(L)} = \begin{pmatrix} U_{R\,(L)} \\ D_{R\,(L)} \end{pmatrix}$$

$$\Lambda_u = \begin{pmatrix} \lambda_u & 0 \\ 0 & 0 \end{pmatrix} \quad \Lambda_d = \begin{pmatrix} 0 & 0 \\ 0 & \lambda_d \end{pmatrix},$$

$$\text{ext. source for } \mathcal{L}_\chi : \quad \Phi_\Lambda = \Phi_u \Lambda_u + \Phi_d \Lambda_d\,, \quad \Phi_\Lambda \to L \Phi_\Lambda R^\dagger$$

$$\text{MSSM Higgs fields} : \qquad \Phi_q = \frac{1}{\sqrt{2}}(\sigma_q + f_q + 2i\pi_q^a\,T^a), \quad q = u, d.$$

$$\pi^a,\ \sigma : \quad \Sigma_\sigma = \frac{\sigma + f}{\sqrt{2}} \mathrm{Exp}\left[\frac{i2\pi^a T^a}{f}\right], \quad \Sigma \to L \Sigma R^\dagger$$

$$f = f_{\rm TC} \text{ in chiral limit}, \quad m_U = m_D = 0$$

- Chiral Lagrangian for QCD-like TC:

$$\mathcal{L}_\chi = \frac{Z_1}{2}\mathrm{Tr}\left(D_\mu \Sigma_\sigma^\dagger D_\mu \Sigma_\sigma\right) + \frac{Z_3}{2\sqrt{2}\pi}\left[\mathrm{Tr}\left(D_\mu \Sigma_\sigma^\dagger D_\mu \Phi_{\Lambda_1}\right) + \mathrm{h.c.}\right] + \frac{1}{2}\sum_{q=u,d}\mathrm{Tr}\left(D_\mu \phi_q^\dagger D_\mu \phi_q\right)$$
$$+Z_2 4\sqrt{2}\,\pi f^2\left[\mathrm{Tr}\left(\Phi_{\Lambda_1}\Sigma_\sigma^\dagger\right) + \mathrm{h.c.}\right] + 2Z_4\left[\mathrm{Tr}\left(\Phi_{\Lambda_1}\Sigma_\sigma^\dagger\right) + \mathrm{h.c.}\right]^2,$$

  - $Z_i[\hat{m}]$ are dimensionless functions of $\hat{m} \equiv (m_U + m_D)/2$ and the low energy chiral Lagrangian constants
  - condensate at $O(p^2)$: $\langle \bar{T}T\rangle_0 = -8\pi f^3\, Z_2[\hat{m} = 0]$
  - TC pion mass at $O(p^2)$: $m_{\pi\pi}^2 = 16\pi^2 Z_2[\hat{m} = 0]\, f\, \hat{m}$ (GMOR relation)
  - the chiral symmetry breaking scale $\Lambda_\chi \sim 4\pi f$ in NDA

- scaling to TC from QCD:
  - use low energy $O(p^4)$ constants from $n_f = 2$ lattice QCD   ETM 0911.5061
  - include $1/N$ scalings to account for $N_{\rm TC} = 2$ vs $N_c = 3$
  - for massive quantities scale up by powers of $f/f_\pi^{\rm QCD}$
  - for $\hat{m}/f > 1$ use linear extrapolation of chiral logs (analog of $\hat{m} \gtrsim m_s$ in QCD)
  - included multiplicative fudge factors for the $Z_i, \quad \in [0.5, 1.5]$
    - to account for uncertainties from $1/N$ scaling, higher orders in p^2, $\hat{m}/f > 1$, back reaction of Yukawa couplings on TC condensate,...
    - true theory uncertainties probably require larger ranges for the fudge factors

- The Z_3 term $\Rightarrow$ kinetic mixing between the TC and fundamental pions, and between the TC and fundamental neutral scalars at $\geq O(p^4)$
  - transform to canonical bases

- The Z_2, Z_4 terms $\Rightarrow$ TC pion mass; mass mixing between the TC and fundamental pions; mass mixing between the TC and fundamental scalars at $\geq O(p^2)$
  - diagonalization of the scalar mass matrix yields the (light) Higgs and an intermediate mass Higgs: primarily fundamental σ_u, σ_d,
  - a heavy Higgs: primarily composite σ

- for the pure TC σ mass term, we scale up NJL-type σ_{QCD} mass e.g. Klevansky '92; Hatsuda, Kunihiro '94

$$m_\sigma^2 = (2M_{\rm c})^2 \frac{f^2}{f_\pi^2} \frac{3}{N_{\rm TC}} + c\, m_\pi^2\,, \quad c = O(1)$$

  - took QCD "constituent" quark mass $M_c \in [0.25, 0.40]$ GeV, $\quad c \in [0.35, 1.0]$
  - yields $m_\sigma \lesssim m_\rho$ (come to ρ mass later)

calculability of loop effects?

- pion loop effects are calculable if the chiral expansion parameter

$$\frac{M^2}{\Lambda_\chi^2} \approx \frac{\hat{m}}{2\pi f} << 1$$

  - relevant for ΔS, ΔT

- ρ, a_1 loops are not calculable because $\quad m_{\rho,a_1}/\Lambda_\chi \sim 1$
  - $h \to \gamma\gamma$ not calculable (a drawback, but significant range about SM in principle possible)

- parametrize TC induced $h\gamma\gamma$ coupling using NDA

$$\frac{\alpha}{2\pi}\frac{1}{\Lambda}\kappa\frac{\lambda_u c_u + \lambda_d c_d}{\sqrt{2}} h A^{\mu\nu} A_{\mu\nu}$$

where $h = c_u \sigma_u + c_d \sigma_d + c_\sigma \sigma$ and $\kappa = O(1)$. Took

$$\Lambda = 4\pi f, \qquad \kappa \in \pm[0.5, 3]$$

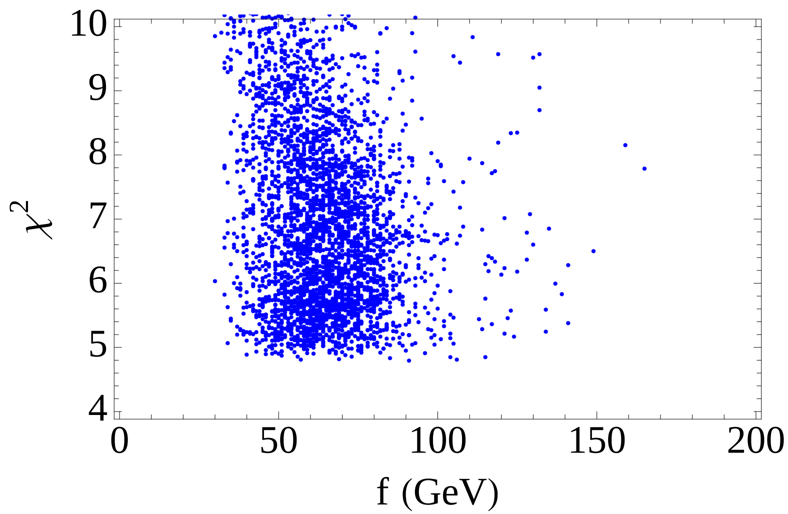
Fit to the Higgs data

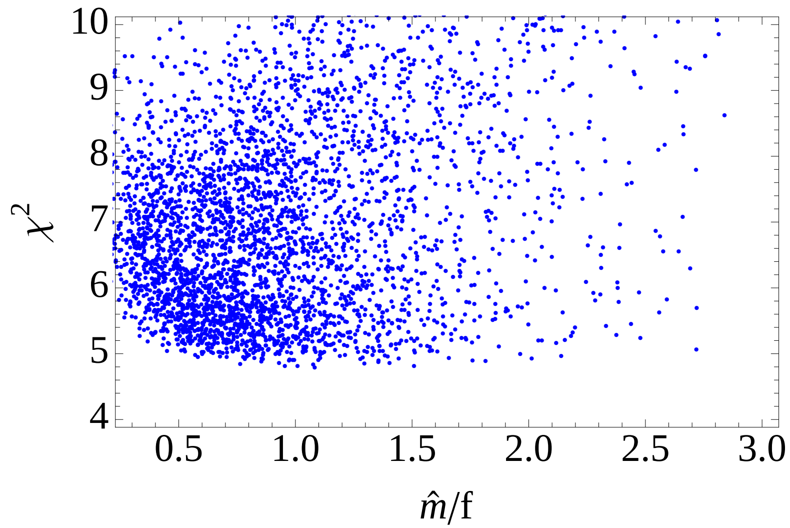
Channel	$(\mu_V\,,\,\mu_F)$	$(\Delta\mu_V\,,\,\Delta\mu_F)$	ρ
ATLAS $\gamma\gamma$	(1.75, 1.62)	(1.25, 0.63)	-0.17
CMS $\gamma\gamma$	(1.48, 0.52)	(1.33, 0.60)	-0.48
ATLAS ZZ	(1.2, 1.8)	(3.9, 1.0)	-0.3
CMS ZZ	(1.7, 0.8)	(3.3, 0.6)	-0.7
ATLAS WW	(1.57, 0.79)	(1.19, 0.55)	-0.18
CMS WW	(0.71, 0.72)	(0.96, 0.32)	-0.23
ATLAS $\tau\bar{\tau}$	(1.67, 0.97)	(1.14, 1.86)	-0.49
CMS $\tau\bar{\tau}$	(1.28, 0.46)	(0.66, 0.81)	-0.42
Combined $Vh,\, h \to b\bar{b}$	(0.9, -)	(0.3, -)	-
Combined $t\bar{t}h,\, h \to b\bar{b}$	(-, -0.1)	(-,1.8)	-

Current signal strengths with their uncertainties and correlations for the 126 GeV resonance used in the fit. 18 measurements

Preliminary

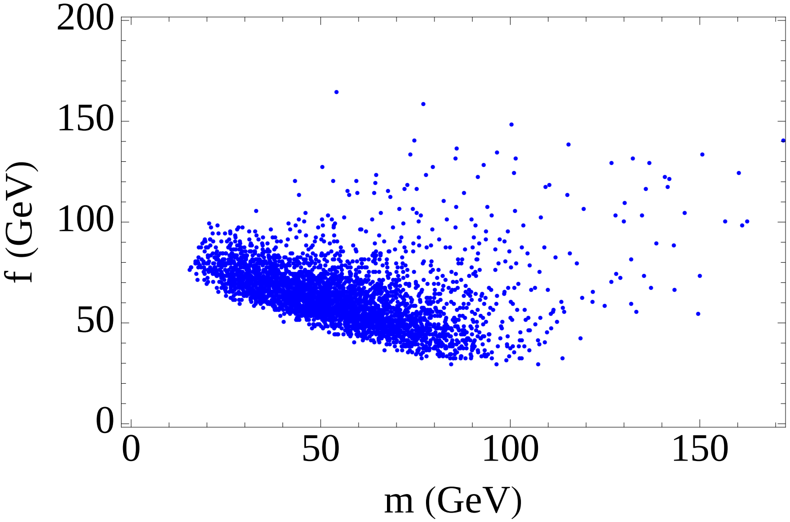
- 18 measurements, 6 parameters ($m^2_{H_u}$, $m^2_{H_d}$, $B\mu$, λ_u, λ_d, f), 2 constraints (v_W, m_h) $\Rightarrow$ 14 d.o.f. + 4 fudge factors for Z_i, 2 fudge factors for m_σ
- restricted $\tan\beta \in [1/3, 3]$, and $m_U, m_D > 0$ with $|m_U - m_D| < 100$ GeV
- SM $\chi^2 \approx 5.8$
  - the scan has $\chi^2_{\min} \approx 4.8$

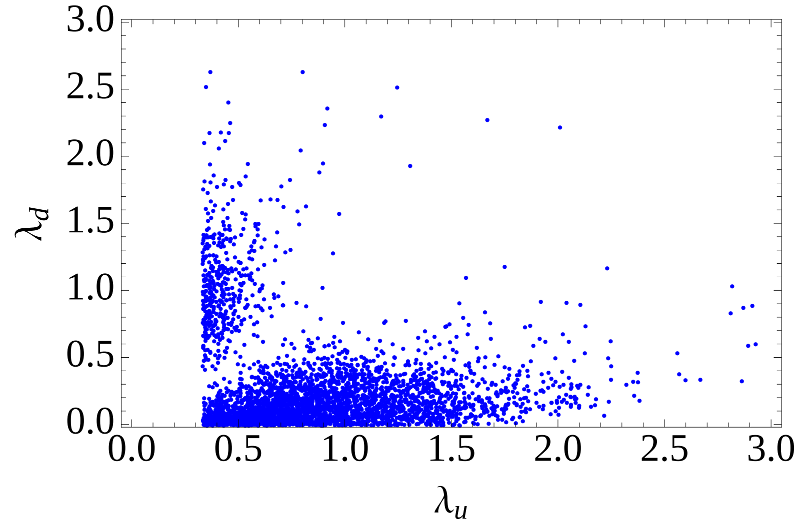




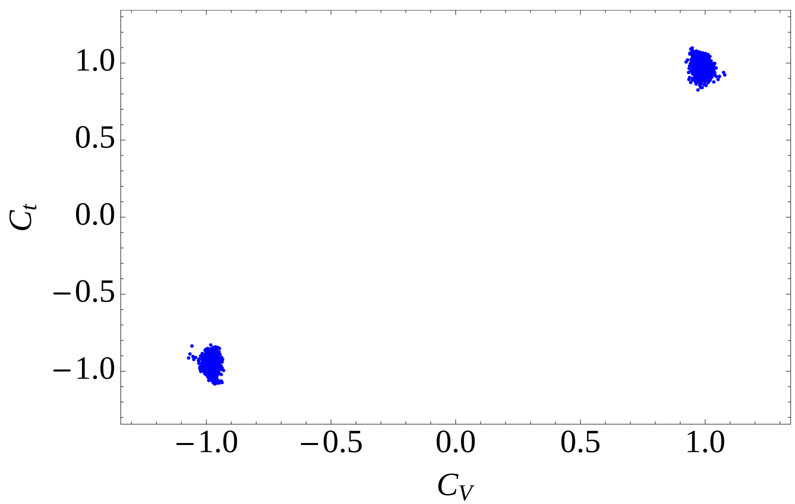
throughout, χ^2 plots are for points within 1σ of $\chi^2_{\min}$

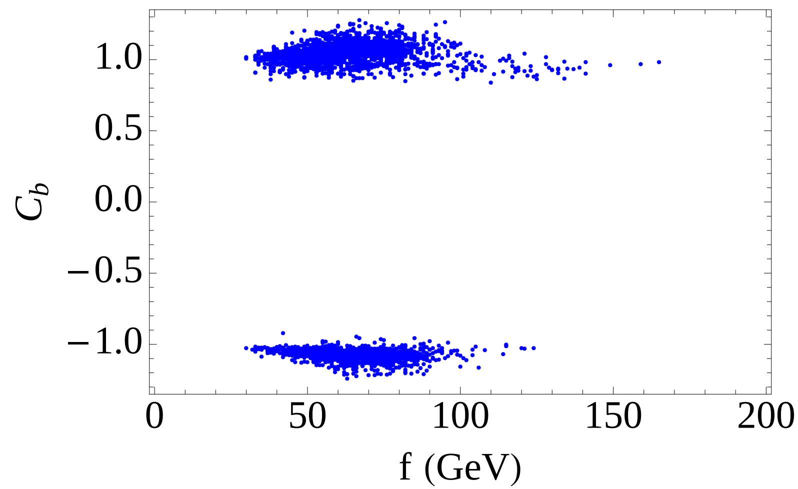
- f vs. $\hat{m}$, and the technifermion Yukawa couplings λ_u vs. λ_d:





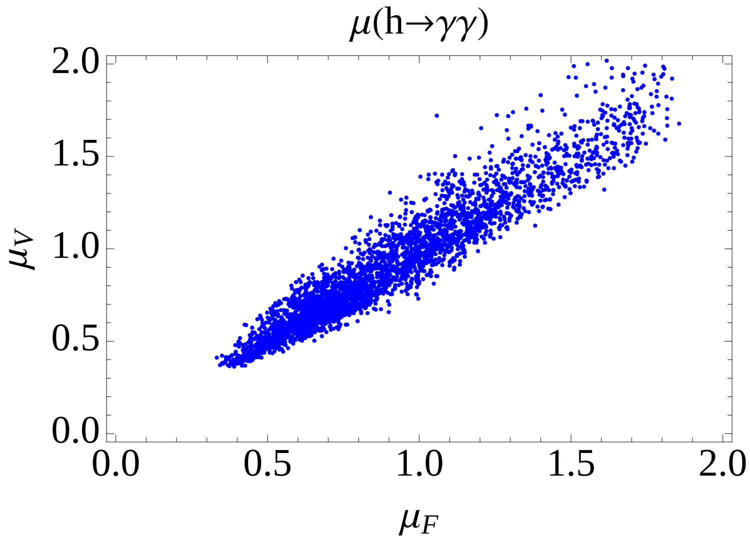
- c_V and c_t are ratios of hVV and htt couplings to their SM values

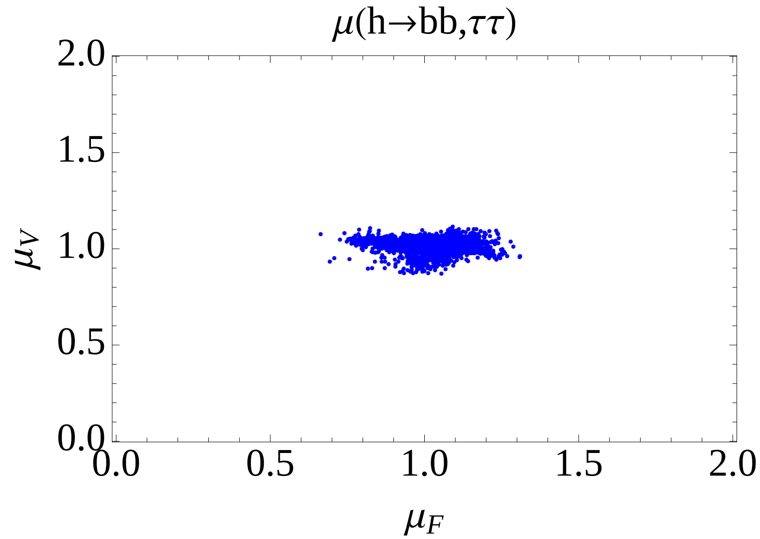




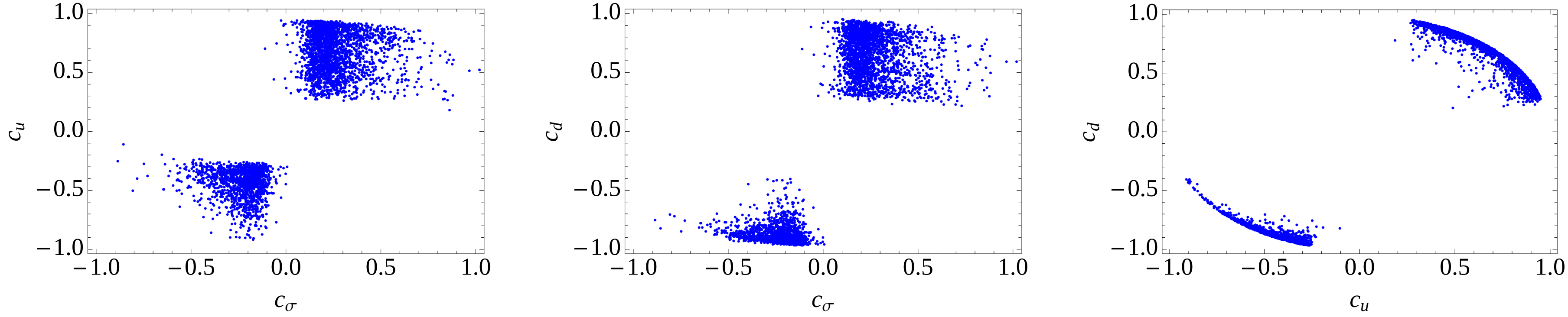
- $h\,V\,V$ and $h\bar{t}t$ couplings are SM-like; $h\bar{b}b$, $h\bar{\tau}\tau$ ($c_b = c_\tau$) exhibit mild variation, consistent with $\tan\beta = O(1)$

$h \to \gamma\gamma$ signal strengths (left); $h \to bb, \tau\tau$ signal strengths (right),
for vector boson fusion (μ_V) vs. gg (μ_F)

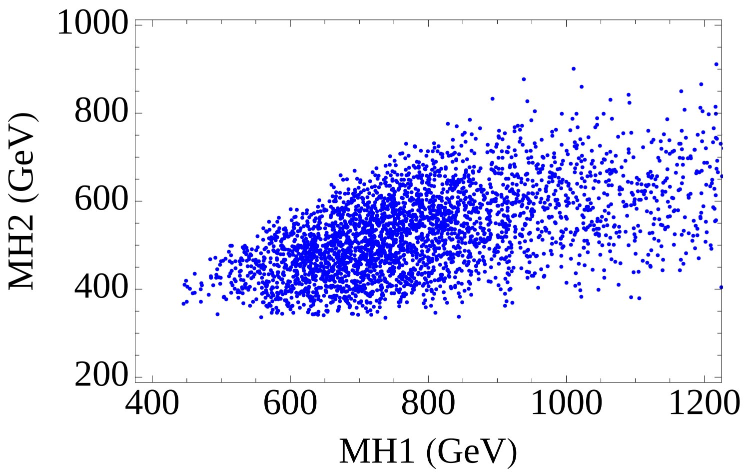




- Higgs admixtures with σ_u, σ_d, σ: $\quad h = c_u\sigma_u + c_d\sigma_d + c_\sigma\sigma$



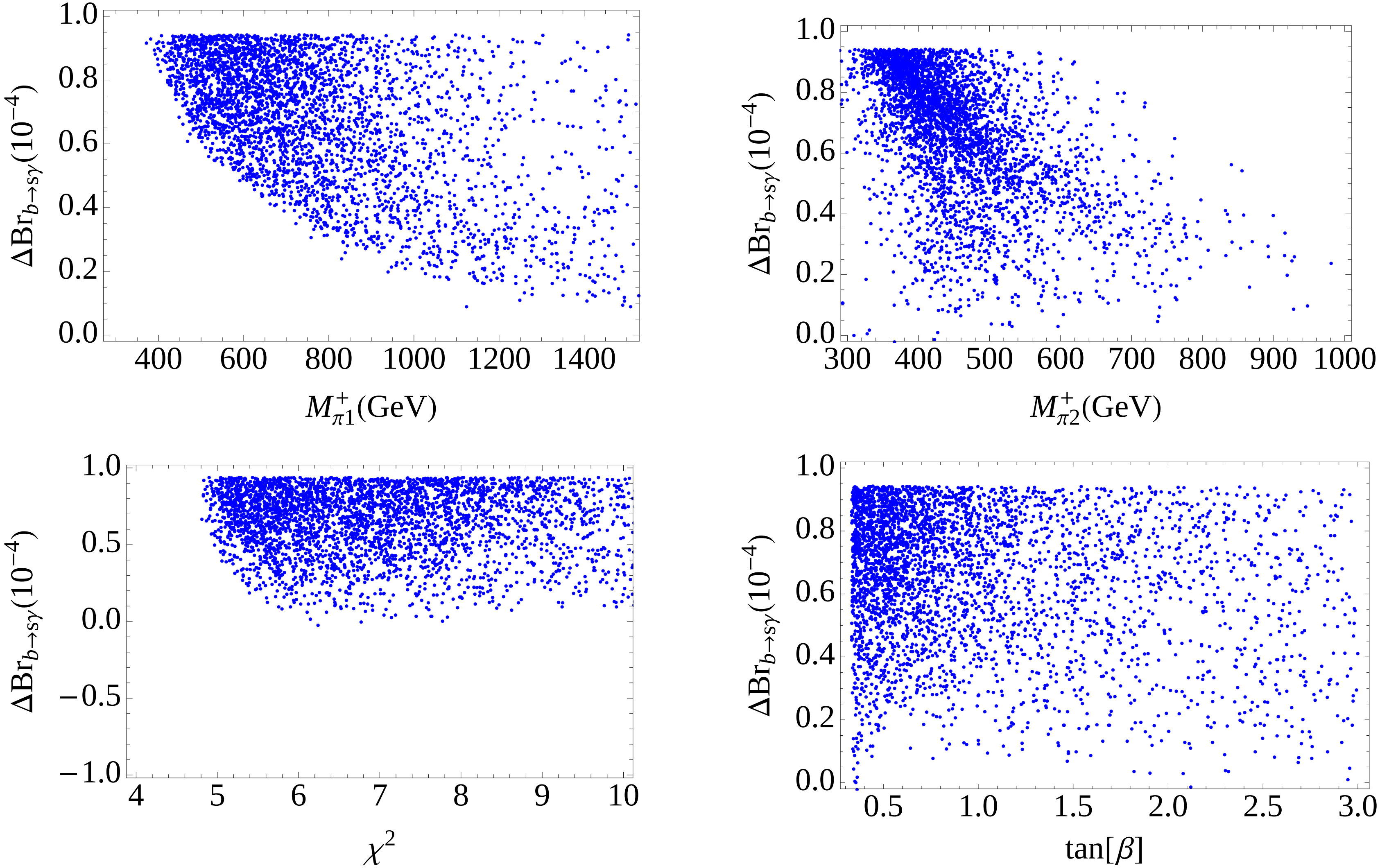
- Heavy Higgs eigenvalues



$b \to s\gamma$

- presence of charged pions means we should check $\mathrm{Br}(B \to X_s\gamma)$. Define

$$\Delta\mathrm{Br} \equiv \mathrm{Br}_{\mathrm{BTC}} - \mathrm{Br}_{\mathrm{SM}}, \quad \text{compare to } \mathrm{Br}_{\mathrm{exp}} - \mathrm{Br}_{\mathrm{SM}} = (0.28 \pm 0.32) \times 10^{-4}$$

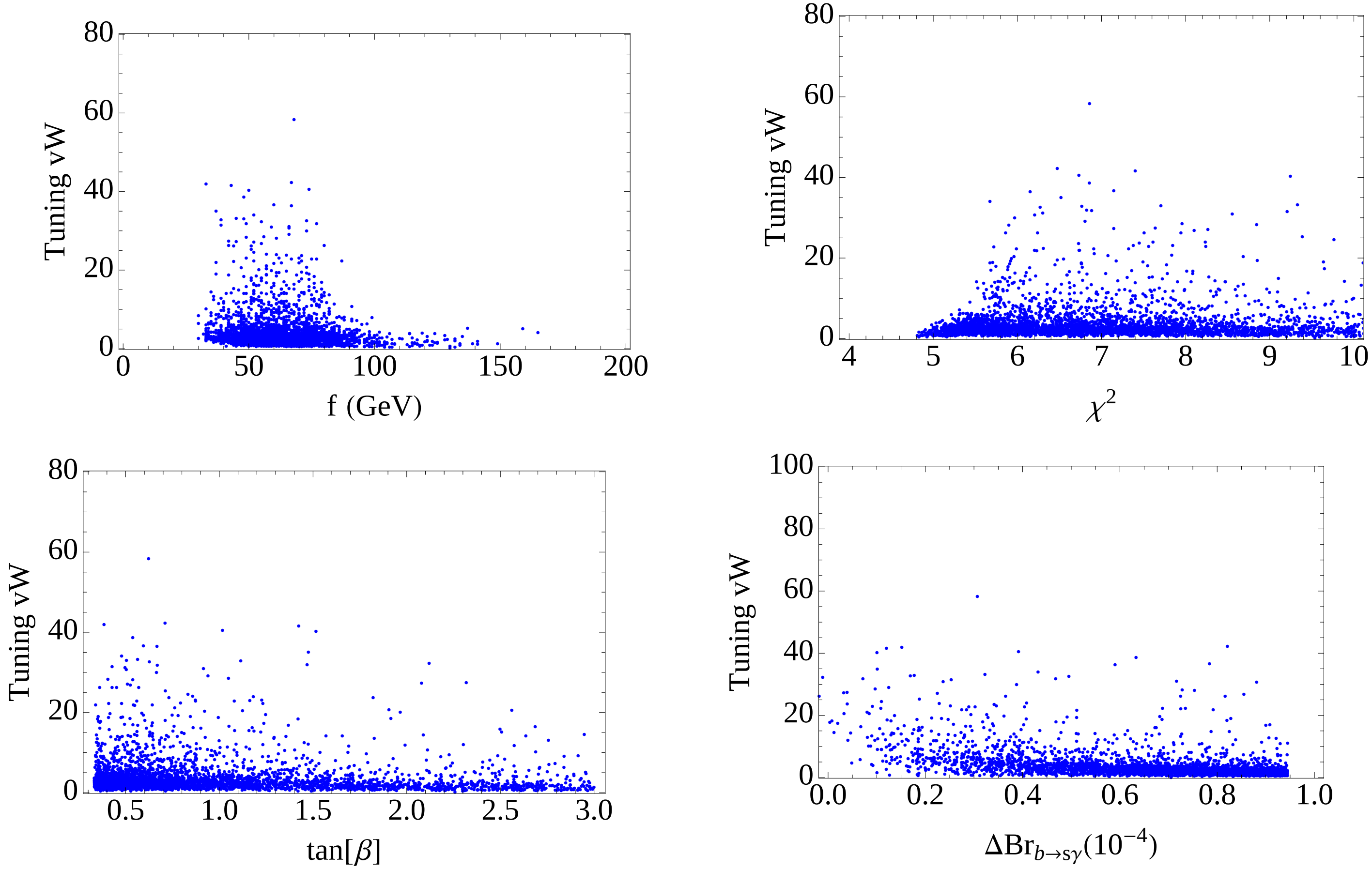


next scan: $\tan\beta > 1$

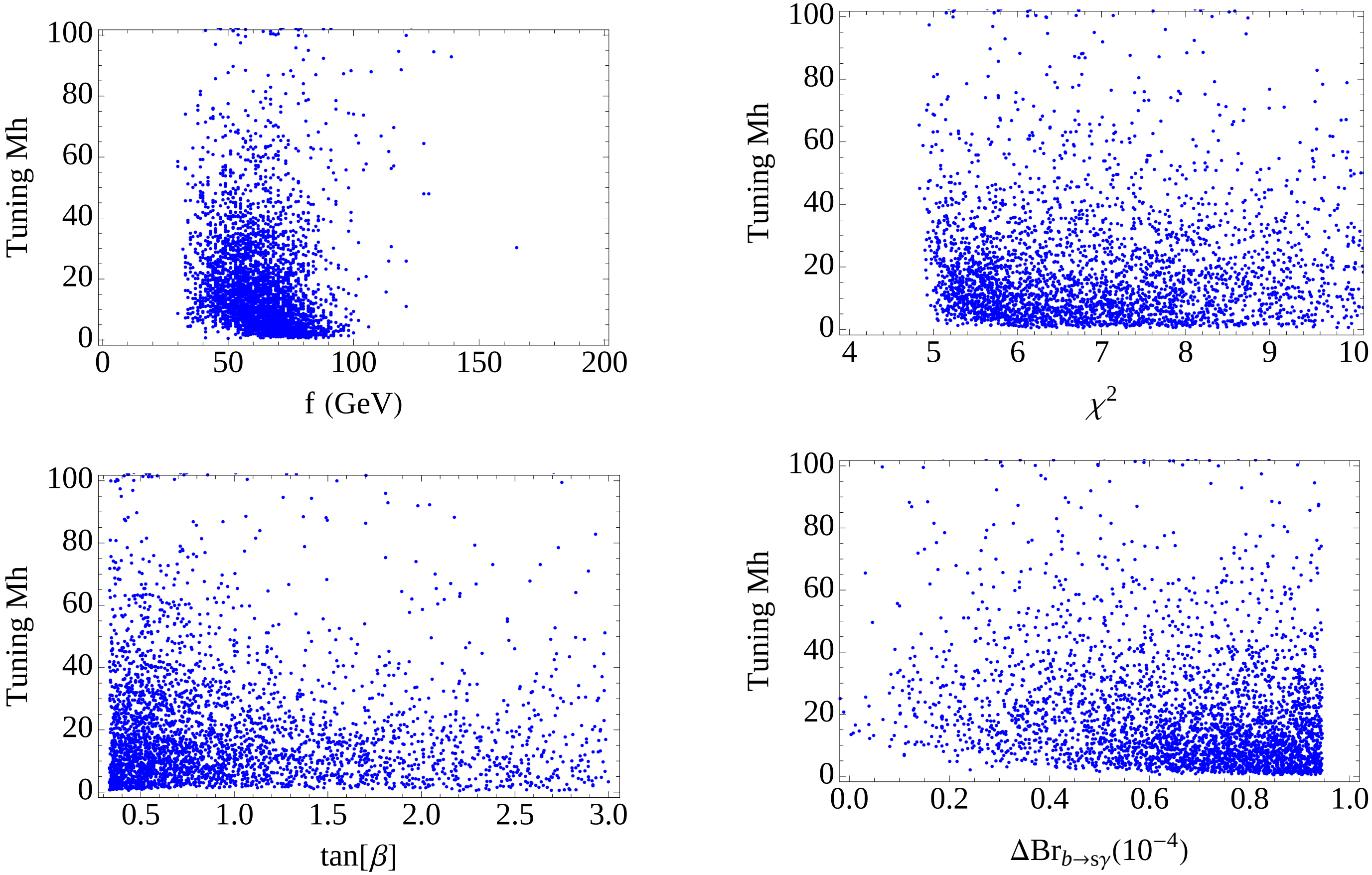
Tuning from the low energy scale perspective

- consider Barbieri-Giudice type measure for a given solution

$$\text{tuning}_{v_W\,(m_h)} = \text{Max}\left[\frac{\partial \log v_W(m_h)}{\partial \log p_i}\right]\,;\quad p_i = f, \lambda_u, \lambda_d, m^2_{H_u}, m^2_{H_d}, B\mu, \text{fudge factors}$$



- confirm that v_W generically does not require significant tuning



- generically, more tuning required for $m_h = 126$ GeV than for v_W, but plenty of solutions can be found with moderate < 10 tuning, e.g. $O(\mathrm{few})$ that are consistent with $\mathrm{Br}(b \to s\gamma)$ (particularly for $\tan\beta > 1$)

ΔS and ΔT away from the chiral limit

- $\Delta S_{\rm tree}$ in the narrow width approximation, due the lowest lying ρ, a_1 resonances

$$\Delta S_{\rm tree} = 4\pi \left(\frac{f_\rho^2}{m_\rho^2} - \frac{f_{a_1}^2}{m_{a_1}^2} \right)$$

  - f_ρ is well known in QCD, f_{a_1} is not so well known
  - take $f_{a_1} = 160$ MeV: average of 152 MeV from $\mathrm{Br}(\tau^+ \to \nu_\tau \pi^+ \pi^+ \pi^-)$ (Isgur et al. '89 + updated Br measurement) and 168 MeV from QCD sum rules (K.C. Yang '07)

$$\Rightarrow \quad \Delta S_{\rm tree} \approx \left(.25 \, \frac{N_{\rm TC}}{3} \right)$$

    agrees with $\Delta S_{\rm tree}$ using Weinberg's sum rules in narrow resonance approximation Peskin,Takeuchi

  - but the $\Delta S_{\rm tree}$ estimates have essentially been obtained in the chiral limit $m_{u,d} << f$

- what happens far from the chiral limit, as in BTC?
  - based on QCD, lattice, we know that m_ρ must increase more rapidly than f_ρ with increasing $\hat{m}$
  - m_{a_1} is $\approx 50\%$ larger than m_ρ (due to P-wave quark energy)
    - $\Rightarrow$ slower relative increase in m_{a_1} than m_ρ, with increasing $\hat{m}$
- Therefore, S_{tree} could decrease significantly with increasing $\hat{m}$!

- get an idea of the effect from lowest lying $[s\bar{s}]$ vector V_s and axial vector A_s resonance masses and decay constants. Ideally, would evaluate

$$\Delta S'_{\rm tree} = 4\pi \left(\frac{f_{V_s}^2}{m_{V_s}^2} - \frac{f_{A_s}^2}{m_{A_s}^2} \right)$$

  - $f_{V_s} = f_\phi, \quad m_{V_s} = m_\phi$ to very good approximation
  - A_s is $O(10\%)$ admixture of $f_1(1285)$ and $f_1(1420)$; heavier $f_1(1420)$ is dominantly $[\bar{s}s]$ $\Rightarrow$ $m_{A_s} < m_{f_1(1420)}$
  - but $f_{A_s} > f_{a_1}$

$$\Rightarrow \quad \Delta S'_{\rm tree} < 4\pi \left(\frac{f_\phi^2}{m_\phi^2} - \frac{f_{a_1}^2}{m_{f_1(1420)}^2} \right) \approx 0.14 \;\; (N_c = 3)$$

compared to chiral limit $\Delta S_{\rm tree} \approx 0.25 \;\; (N_c = 3)$

- lattice data for f_{η_h}, for variation of M_{η_h} between M_{η_c} and M_{η_b} gives an excellent approximation for the variation of the quarkonium decay constant between the J/ψ and Υ HPQCD, 1207.0994

- combining with known f_ρ, f_ω, f_ϕ in QCD get an approximate extrapolation for quarkonium decay constants over a wide range of $\hat{m}$. Rescale to BTC via scale factor $f/f_\pi \Rightarrow$

$$f_\rho[\hat{m}] = f_\rho^{\rm QCD} \frac{f}{f_\pi} \mathcal{F}\left[\frac{m_\rho[\hat{m}]}{m_\rho[0]}\right]$$

- the dependence of the BTC ρ and a_1 masses on $\hat{m}$ approximated by scaling from a naive quark model estimate of the QCD light vector mass dependence on $\hat{m}$:

$$m^2_{\rho\,(a_1)}[\hat{m}] \approx m^2_{\rho\,(a_1)\,QCD} \left(\frac{f}{f_\pi}\right)^2 \frac{3}{N_{TC}} + 2\mu_{V(A)} \frac{f}{f_\pi} \sqrt{\frac{3}{N_{TC}}}\,\hat{m}$$

with $\mu_V, \mu_A \approx 2.2$ GeV from naive quark model QCD fit.

- For illustration, will assume TC f_{a_1} has same extrapolation as TC f_ρ, i.e.

$$f_{a_1}[\hat{m}] = f_{a_1}^{\rm QCD} \frac{f}{f_\pi} \mathcal{F}\left[\frac{m_{a_1}[\hat{m}]}{m_{a_1}[0]}\right]$$

- $\Delta T_{\rm tree}$ from

$$\mathcal{L} \sim \left(\mathrm{Tr}\left[\Phi_\Lambda D^\mu \Sigma^\dagger\right]\right)^2 \quad \Rightarrow \quad \Delta T_{\rm tree} \sim \frac{1}{16\pi^2\alpha}\frac{(m_U - m_D)^2}{v_W^2}$$

  - e.g. $\Delta T_{\rm tree} < 0.10$ corresponds to $|m_U - m_D| \lesssim 90$ GeV
  - imposed $|m_U - m_D| < 100$ GeV on the scan

ΔS_{loop}, ΔT_{loop} from loops with (pseudo) scalars, Z, W

- including the TC σ, we can directly carry over the results for S and T at one loop in multi-Higgs doublet models Grimus, Lavoura Ogreid, Osland '08
  -with three doublets in BTC

- including the SM subtraction yields scale independent results

- for simplicity we have not included loops containing the ρ, a_1. However, with the SM scale dependent contribution already subtracted in ΔS_{loop}, we can consistently approximate the TC resonance contributions at tree-level
  - the scale dependence is removed because the σ is included
  - contributions of loops with vectors to ΔS can be neglected Orgogozo, Rychkov

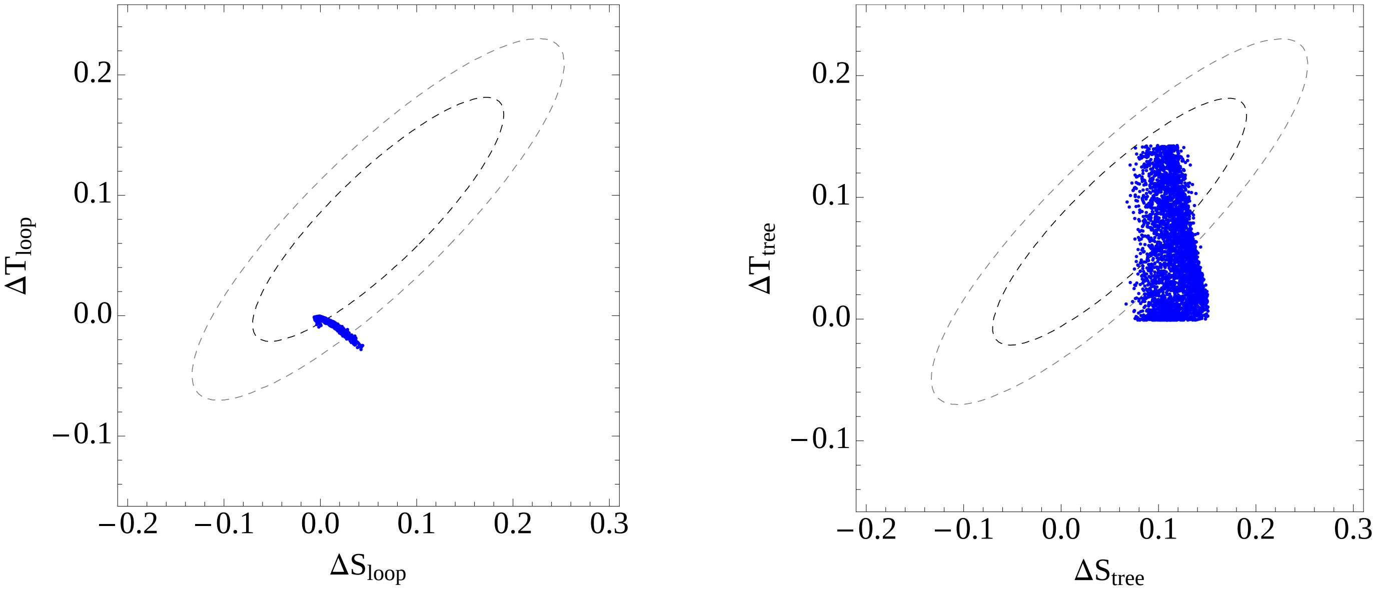
- $\Delta T_{\rm loop}$ from to $\pi^+ - \pi^-$ mass splitting
  - previous authors considered $\pi^+ - \pi^-$ mass splitting via the operator

$$f^2 \mathrm{Tr}\left(\left[\Phi_\Lambda \Sigma^\dagger\right] - \mathrm{h.c.}\right)^2$$

  - 1-loop diagrams with π's, Higgs then yield a scale dependent (log-divergent) contribution to ΔT - interpreted as logarithmic enhancement by setting the cutoff scale to $\Lambda_\chi \sim 4\pi f$.
  - therefore thought to dominate over $\Delta T_{\rm tree}$
- instead the $\pi^+ - \pi^0$ mass splitting should be attributed to $\pi - \eta'$ mixing - this should be the dominant source.
  - adapting the QCD $\pi - \eta - \eta'$ mixing formalism in Kroll '08 to $\pi - \eta'$ mixing in BTC (scaling from QCD), and also including the η' in $\Delta T_{\rm loop}$ yields finite, negligible corrections to $\Delta T < 0.001$
  - therefore can ignore the effect of the η' or $pi^+ - \pi^0$ mass splitting

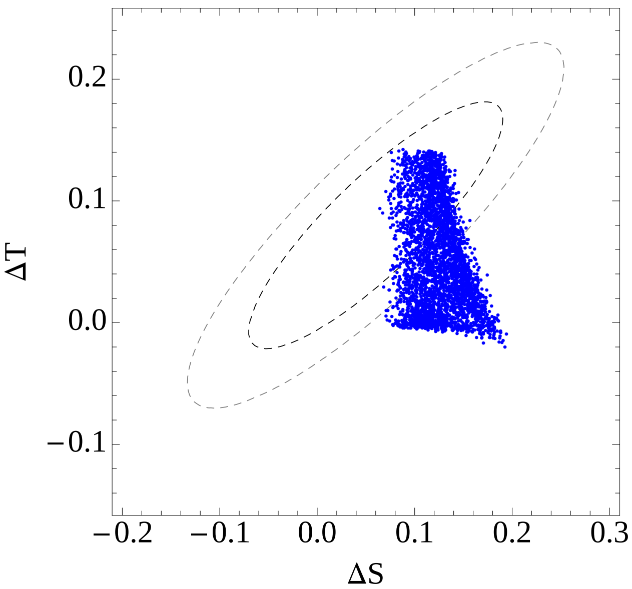
Results for ΔS, ΔT in BTC

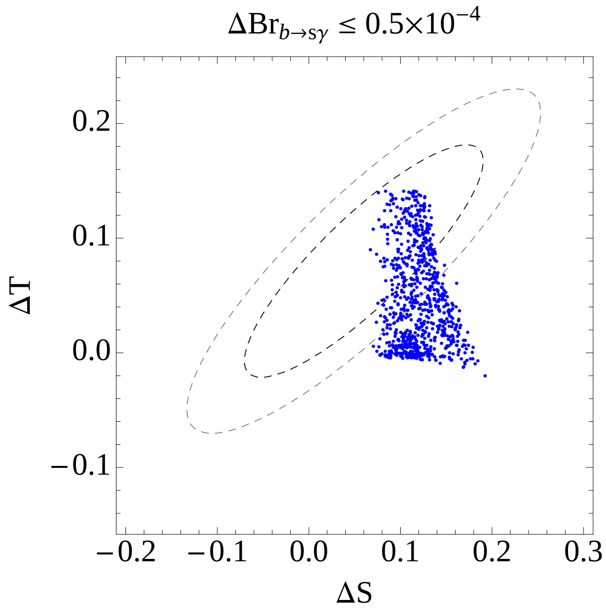
- the loop and tree contributions separately:



1σ and 2σ ellipses from Ciuchini et al

- totals of loop and tree:



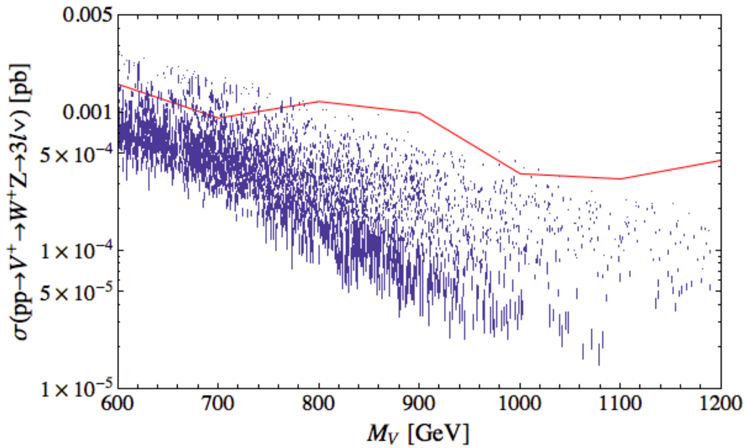


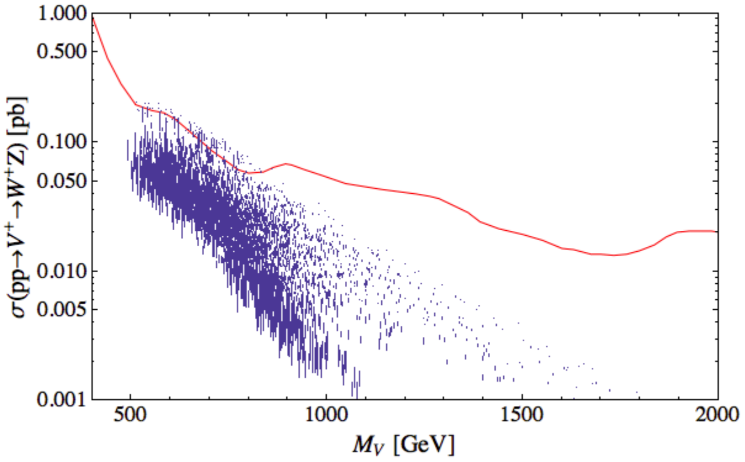
- BTC is a technicolor example which can satisfy the constraints on S and T at 1σ via QCD-like dynamics,
  - no need to invoke unproven conjectures about exotic strong interactions, e.g. conformal or walking dynamics
  - this is because BTC is realized away from the chiral limit

Vector phenomenology

- employ chiral Lagrangian formalism for vectors Ecker et al. '89

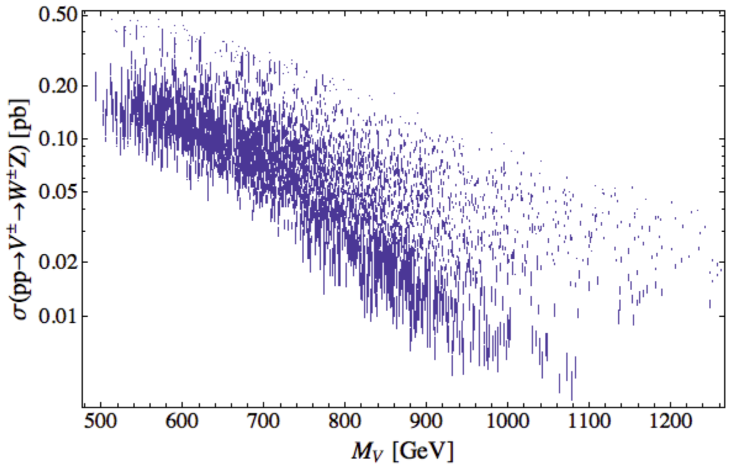
- for now consider LHC bounds on Drell-Yan production $\sigma(pp \to \rho^{\pm} \to W^{\pm}Z)$
- use CMS 19.6 fb^{-1} $W' \to WZ$ trilepton search at 8 TeV CMS PAS EXO-12-025; ATLAS 20 fb^{-1} $W' \to WZ$ $\ell\ell q\bar{q}$ search at 8 TeV 1409.6190
  - CMS and ATLAS present bounds for narrow W'
  - we compare to $pp \to \rho \to WZ$ cross section in ρ narrow width approximation
  - the ρ width is typically $\lesssim 5\%$, so reasonable approximation.
  - Taking into account the ρ width only weakens the constraints

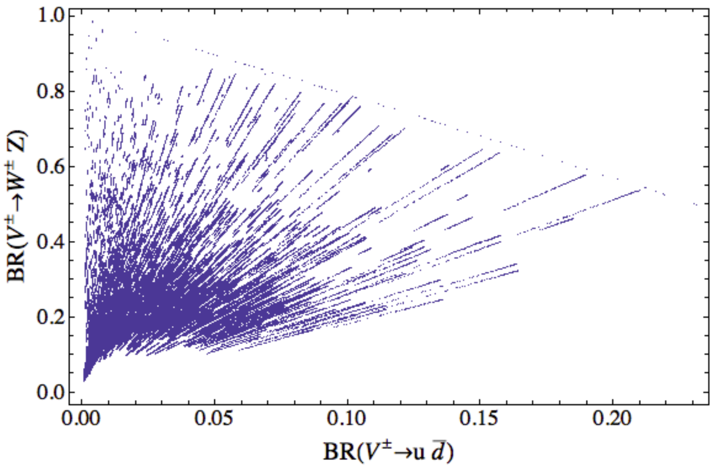


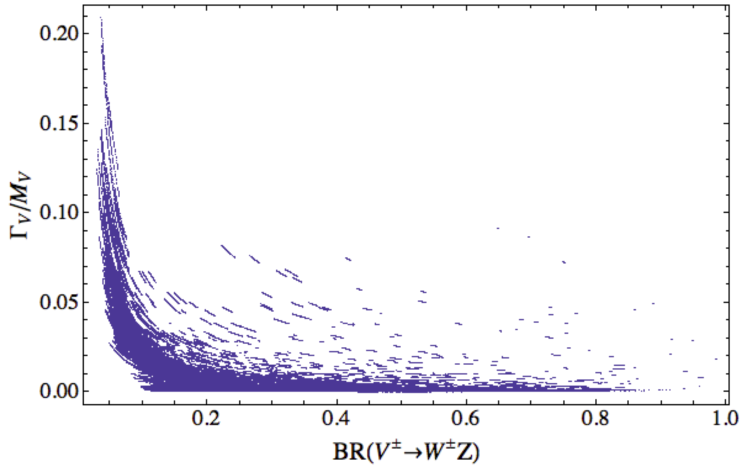


Comparison of $\sigma(pp \to \rho \to WZ)$ to CMS bound (left), ATLAS bound (right)
$\Rightarrow$ predicted cross sections typically lie $O(\mathrm{few}-10)$ below LHC bounds, except at lower m_ρ.

$\sigma(pp \to \rho \to WZ)$ at 14 TeV







- reason for weak bounds: $\rho f f$ coupling $\sim f_\rho/m_\rho$ and ρWW coupling $\sim m_\rho/f_\rho$. therefore $\mathrm{Br}(\rho \to \bar{u}d)$ is small
  - in narrow width approximation, partonic cross section

$$\sigma(u\bar{d} \to \rho \to WZ) \approx \frac{4\pi^2}{3}\frac{\Gamma_\rho}{m_\rho}\mathrm{Br}(\rho \to u\bar{d})\mathrm{Br}(\rho \to WZ)$$

- Sensitivity to the ρ (and σ) in WW scattering is probably more promising

Summary

- The Higgs in BTC is dominantly fundamental
- Get very good fit to LHC Higgs phenomenology
  - unfortunately, $h \to \gamma\gamma$ can only be estimated in NDA
- $\mathrm{Br}(b \to s\gamma)$ provides an important constraint
- from the low energy perspective, v_W generically requires little or no tuning; for m_h moderate tuning of $O(\mathrm{few})$ can be obtained, while maintaining consistency with all constraints
- S and T can easily lie within the 1σ ellipse, primarily due to the effect of technifermion masses on the TC resonance contributions

- LHC bounds on Drell-Yan production of the vector resonances $O(\mathrm{few} - 10)$ above predicted cross sections
  - sensitivity to the ρ and σ in WW scattering is interesting to explore in Run-2
- important to study the LHC phenomenology of the heavier Higgs's and charged pions
  Chang, Evans, Luty; Chang, Galloway, Luty, Salvioni, to appear
- we are exploring potential benefits of R-symmetric BTC for
  - linkage of m_{susy} and Λ_{TC}
  - solution of the μ problem via partial compositeness
  - reduced sensitivity to the UV scale due to supersoft properties