A bosonic technicolor update

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Plan

work in progress with S. J. Lee, A. Martin, P. Uttayarat, J. Zupan

- Introduction
- Higgs phenomenology
- S and T away from the chiral limit
- vector phenomenology
- Comments on R-symmetric BTC

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

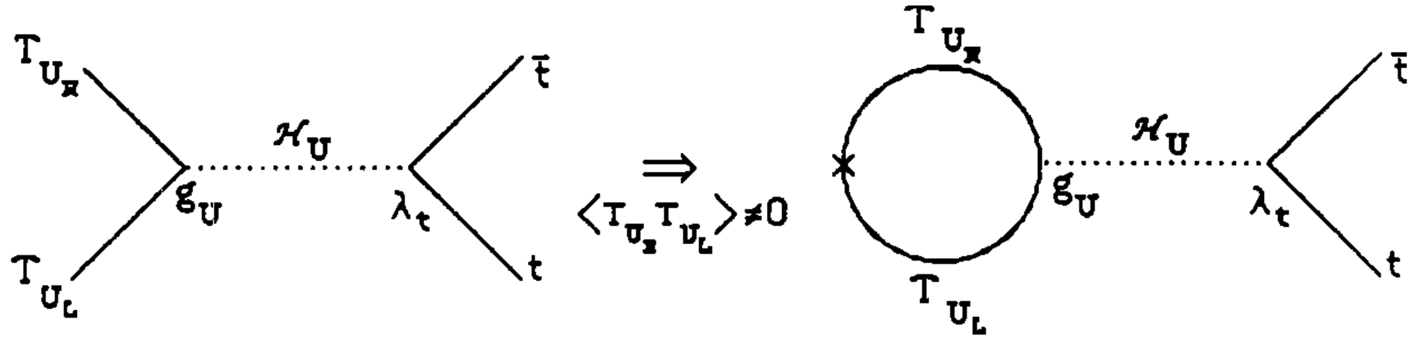
- Higgs VEV's via Yukawa couplings to technifermion condensates

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

  - 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 $m_h \approx 1/2 - 1$ 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

$$\Rightarrow \quad v^2_W \approx f^2_u + f^2_d \gg f^2_{\rm TC}, \quad \text{e.g. } f_{\rm TC} \lesssim 100 \text{ GeV}$$

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

  - $f^2 << v^2_W$, 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,...
  - but, as in MSSM, Higgs mass parameters log sensitive to large SUSY breaking mediation scales
    - unless BTC is $U(1)_R$ symmetric (dirac gauginos), i.e. supersoft

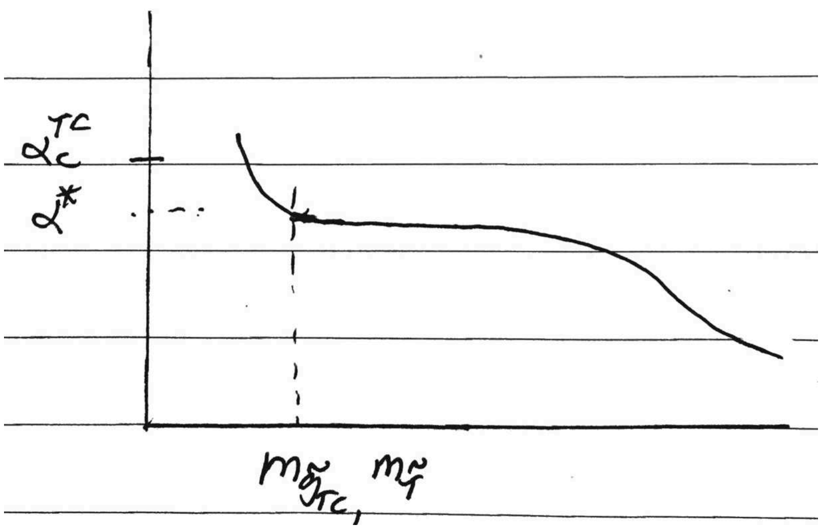
Linking $\Lambda_{\rm TC}$ and $m_{\rm susy}$

- 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

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



Higgs Phenomenology

- $N_{\rm TC} = 2$ allows $M_R \hat{U}_R \hat{D}_R + M_L \hat{T}_L T_L$ superpotential bilinears unless impose $U(1)_B$ baryon number or R symmetry
  - 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 can 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
    - one light higgs h, one heavy Higgs H as in MSSM
    - two charged pions $\pi_1^{\pm}$, $\pi_2^{\pm}$
    - two neutral pions π_1^0, π_2^0

TC Chiral Lagrangian

- Method I: employ 2 flavor $SU(2)_L \times SU(2)_R$ non-linear sigma model chiral Lagrangian $\mathcal{L}_\chi$ to $O(p^4)$ Gasser, Leutwyler + MSSM Higgs scalar potential

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

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

- scalar field content:

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

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

$$\text{TC pions :} \quad \Sigma = \text{Exp}\left[\frac{i2\pi^a T^a}{f}\right], \quad \Sigma \to L \Sigma R^\dagger$$

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

- Chiral Lagrangian for QCD-like TC:

$$\mathcal{L}_\chi = \frac{f^2}{4}\left(1+\frac{M^2}{8\pi^2 f^2}\right)\mathrm{Tr}\left[(D^\mu\Sigma)^\dagger\,(D_\mu\Sigma)\right] + \frac{f^2 B}{2}\left(1+\frac{3M^2}{32\pi^2 f^2}\right)\left(\mathrm{Tr}\left[\Phi_\Lambda\,\Sigma^\dagger\right] + \mathrm{h.c.}\right)$$
$$+\sum_{q=u,d}\frac{1}{2}\mathrm{Tr}\left[(D^\mu\Phi_q)^\dagger(D_\mu\Phi_q)\right] + \frac{B}{32\pi^2}(\bar{l}_4-1)\left(\mathrm{Tr}\left[(D^\mu\Sigma)^\dagger\,(D_\mu\Phi_\Lambda)\right] + \mathrm{h.c.}\right)$$
$$-\frac{B^2}{256\pi^2}\,(\bar{l}_3-1)\left(\mathrm{Tr}\left[\Phi_\Lambda\,\Sigma^\dagger\right] + \mathrm{h.c.}\right)^2$$

  - condensate at $O(p^2)$: $\langle\bar{T}T\rangle_0 = -f^2 B$,
  - TC pion mass at $O(p^2)$: $M^2 = 2\hat{m}B$, $\hat{m} = (m_U + m_D)/2$
  - the chiral symmetry breaking scale $\Lambda_\chi \sim B \sim 4\pi f$ in NDA

- scaling to TC from QCD:
  - obtain B, low energy constants $\bar{l}_3$, $\bar{l}_4$ from $n_f = 2$ lattice QCD ETM 0911.5061
  - for massive quantities scale up by powers of f/f_π^{QCD}
  - include $1/N$ scalings to account for $N_{\mathrm{TC}} = 2$ vs $N_c = 3$
  - for $\hat{m}/f > 1$ use linear extrapolation of chiral logs (analog of $\hat{m} \gtrsim m_s$ in QCD)
  - add multiplicative fudge factors $\in [0.5, 1.5]$ for B/f, $\langle \bar{T}T \rangle / \langle \bar{T}T \rangle_0$, $\bar{l}_3$, $\bar{l}_4$

- Method II: NDA based parametrization for the chiral Lagrangian:

$$\mathcal{L} = Z_1 \frac{f^2}{4} \mathrm{Tr}\left[D_\mu \Sigma^\dagger D_\mu \Sigma\right] + 4\pi f^3\, Z_2\, \left[\mathrm{Tr}\left(\Phi_\Lambda \Sigma^\dagger\right) + \mathrm{h.c.}\right]$$
$$+ \frac{1}{2} \sum_{q=u,d} \mathrm{Tr}\left[D_\mu \phi_q^\dagger D_\mu \phi_q\right] + Z_3 \frac{f}{4\pi} \left(\mathrm{Tr}\left[D_\mu \Sigma^\dagger D_\mu \Phi_\Lambda\right] + \mathrm{h.c.}\right)$$
$$+ f^2\, Z_4 \left(\mathrm{Tr}\left[\Phi_\Lambda \Sigma^\dagger\right] + \mathrm{h.c.}\right)^2$$

$NDA \Rightarrow Z_i = O(1)$. We took

$$Z_{1,2} \in [.3, 3], \quad Z_{3,4} \in [-3, 3]$$

  - Method II yields Higgs pheno fits similar to Method I

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 loops are not calculable because $m^2_{\rho,a_1}/\Lambda_\chi^2 \sim 1$

  - $h \to \gamma\gamma$ not calculable

- parametrize TC induced $h\gamma\gamma$ coupling as

$$\frac{\alpha}{2\pi}\frac{1}{\Lambda}\kappa\frac{\lambda_u \cos\alpha - \lambda_d \sin\alpha}{\sqrt{2}} h A^{\mu\nu} A_{\mu\nu}$$

where $h = \cos\alpha\,\sigma_u - \sin\alpha\,\sigma_d$ and $\kappa = O(1)$ in NDA. Took

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

Fit to the Higgs data

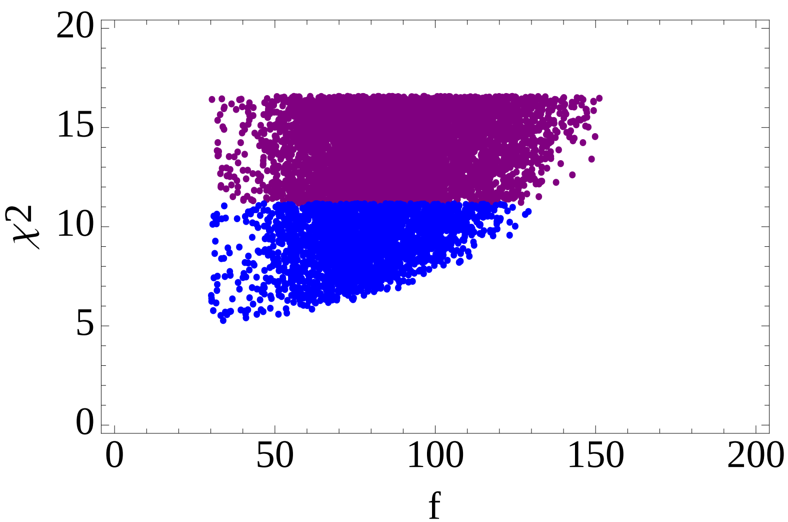
Channel	$(\mu_V\,,\,\mu_F)$	$(\Delta\mu_V\,,\,\Delta\mu_F)$	ρ
ATLAS $\gamma\gamma$	(1.75, 1.62)	(1.25, 0.63)	-0.17
CMS $\gamma\gamma$	(1.48, 0.52)	(1.33, 0.60)	-0.48
ATLAS ZZ	(1.2, 1.8)	(3.9, 1.0)	-0.3
CMS ZZ	(1.7, 0.8)	(3.3, 0.6)	-0.7
ATLAS WW	(1.57, 0.79)	(1.19, 0.55)	-0.18
CMS WW	(0.71, 0.72)	(0.96, 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)	-

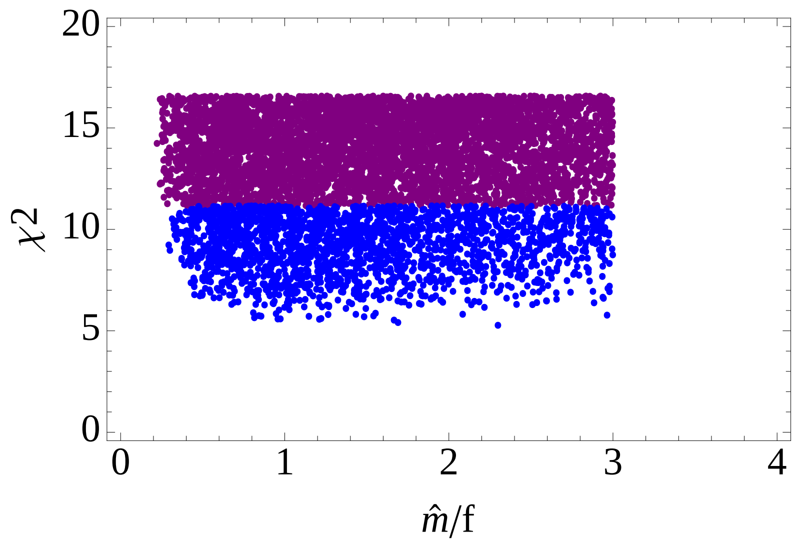
Current signal strengths with their uncertainties and correlations for the 126 GeV resonance used in the fit. 18 measurements

- 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

- The SM $\chi^2 = 5.79$

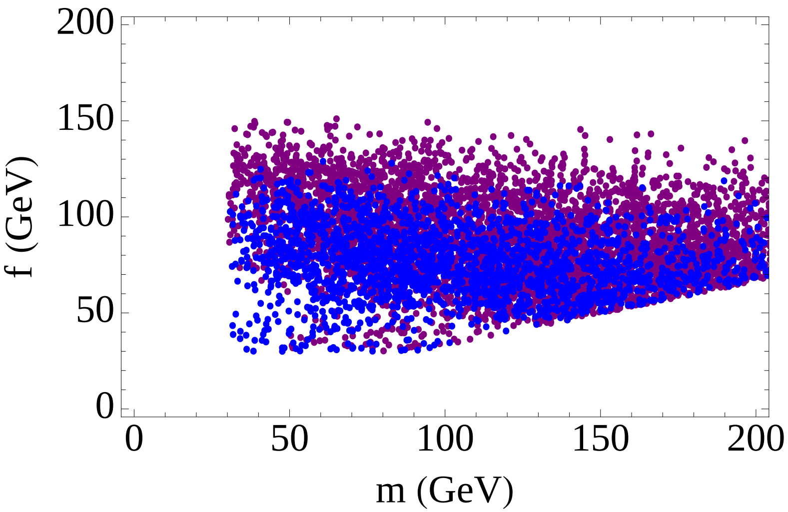
  - both "p^4" and "NDA" scans have $\chi^2_{\rm min} \approx 5.4$

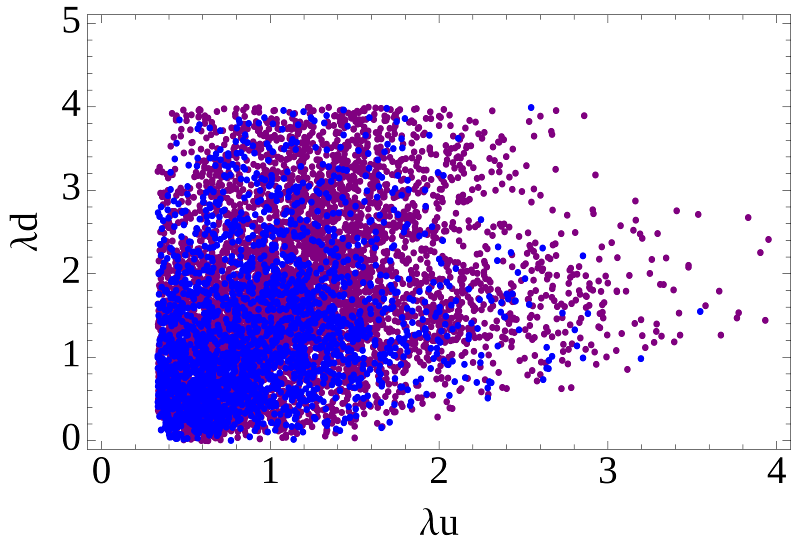




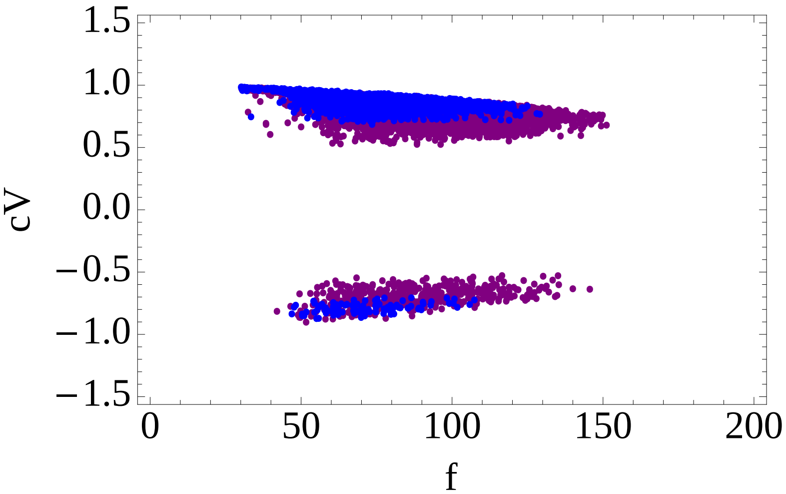
χ^2 plots for "p^4" scan: $\leq 1\sigma$ (blue) and 1σ-2σ (magenta) from $\chi^2_{\rm min}$

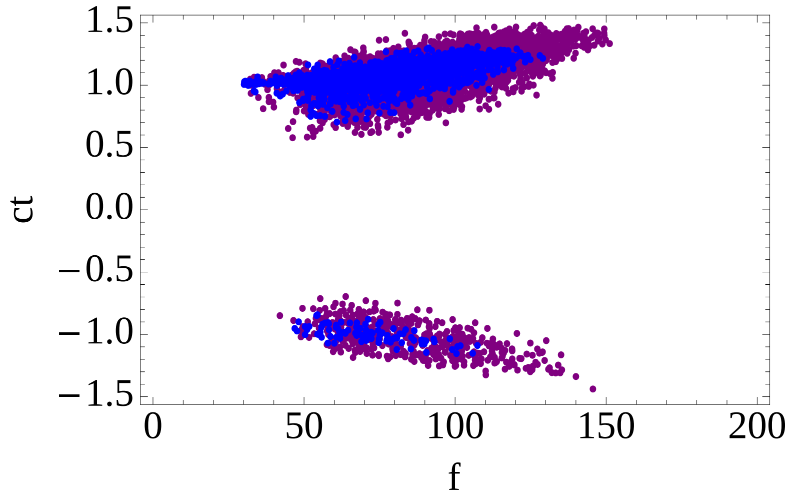
- more plots for p^4 scan:





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

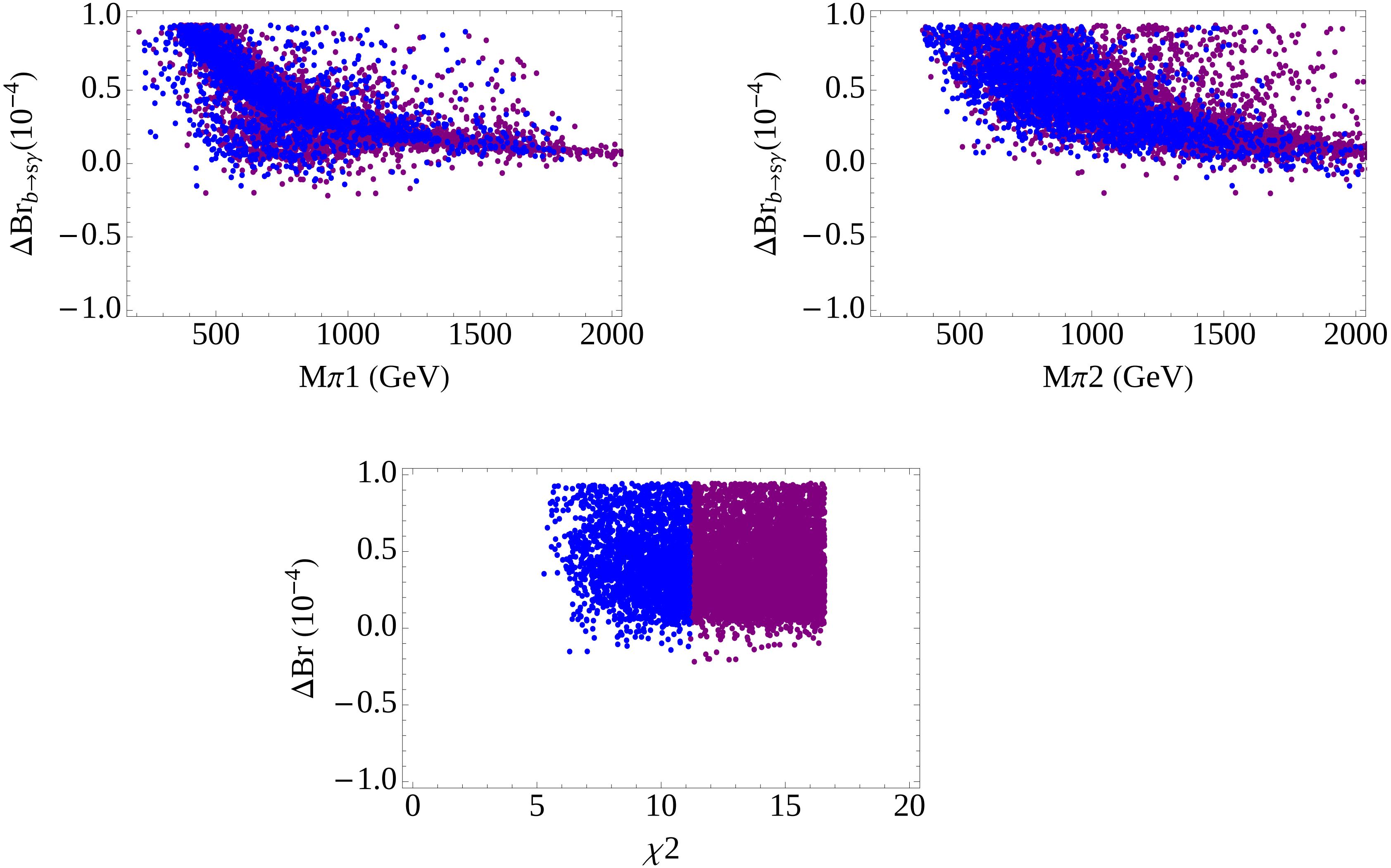




  - see expected trend for $|c_V|$ to increase and $|c_t|$ to decrease with increasing f

$b \to s\gamma$

- presence of charged pions means we should check $\mathrm{Br}(b \to s\gamma)$.
  $\Delta\mathrm{Br} = \mathrm{Br}_{\mathrm{BTC}} - \mathrm{Br}_{\mathrm{SM}}$. For comparison, $\mathrm{Br}_{\mathrm{exp}} - \mathrm{Br}_{\mathrm{SM}} = (0.28 \pm 0.32) \times 10^{-4}$



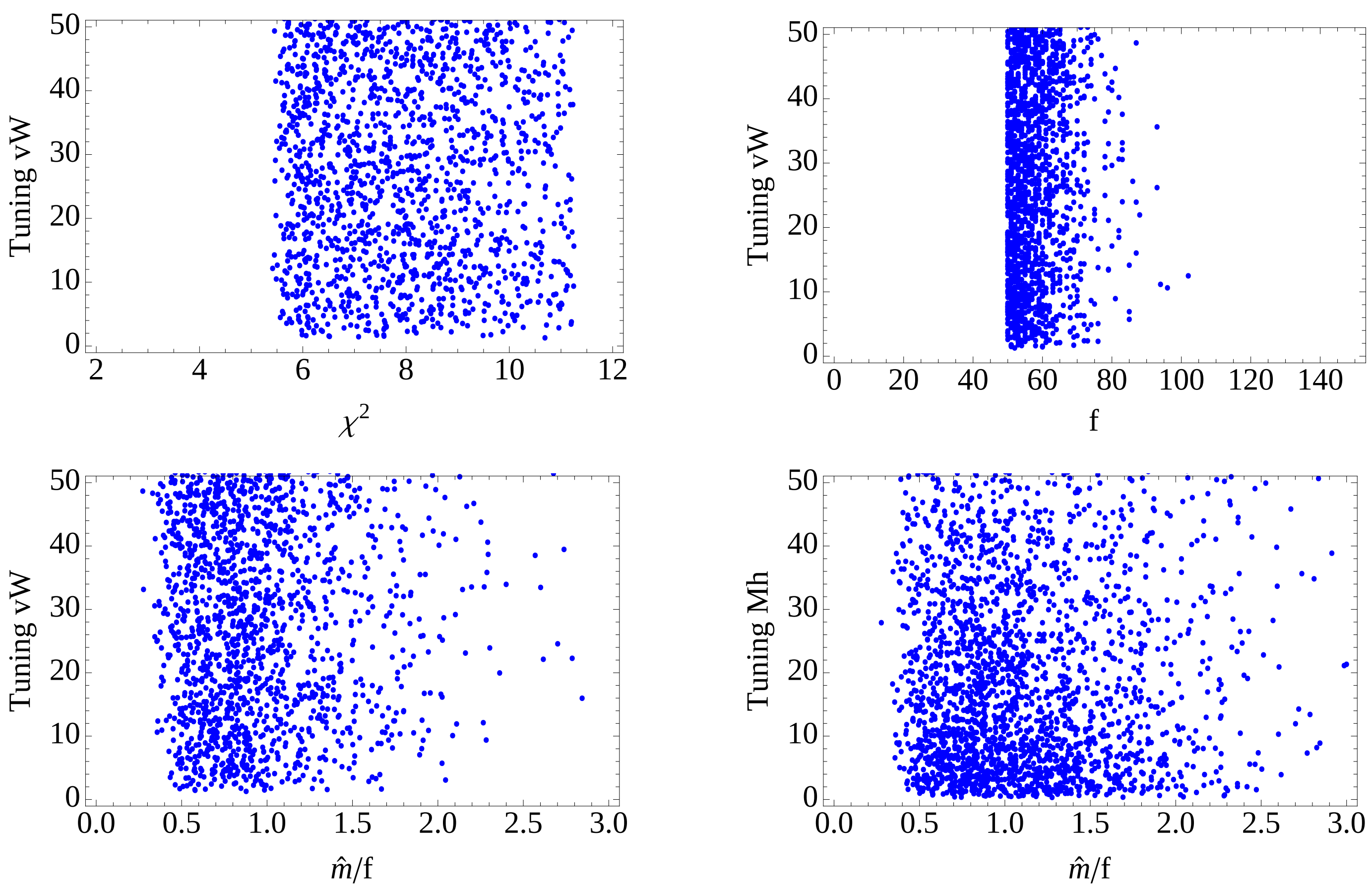
- an important difference with respect to conventional TC models: large $\hat{m}$ from Higgs VEVs means heavy π's

Tuning study in the low energy effective theory

- confirm that $m_h = 126$ GeV and $v_W = 246$ GeV does not require large tuning

- consider Barbieri-Giudice type measure for a given solution

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



above plots from NDA scan, with $f > 50$ GeV

S and T away from the chiral limit

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

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

  - f_ρ is well known in QCD, f_{a_1} is not so well known
  - taking $f_{a_1} = 152$ MeV from $\mathrm{Br}(\tau^+ \to \nu_\tau \pi^+ \pi^+ \pi^-)$ (Isgur et al. '89 + updated Br measurement)

$$\Rightarrow \quad S_{\rm tree} = \left(.27 \, \frac{N_{\rm TC}}{3} \right)$$

  including $1/N$ scaling, consistent with more sophisticated approximation of Peskin&Takeuchi

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

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

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

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

$$\Rightarrow \quad S'_{\rm tree} < 4\pi \left(\frac{f_\phi^2}{m_\phi^2} - \frac{f_{a_1}^2}{m_{f_1(1420)}^2} \right) \approx 0.15 \ (N_c = 3)$$

compared to chiral limit approximation $S = 0.27 \ (N_c = 3)$

- 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

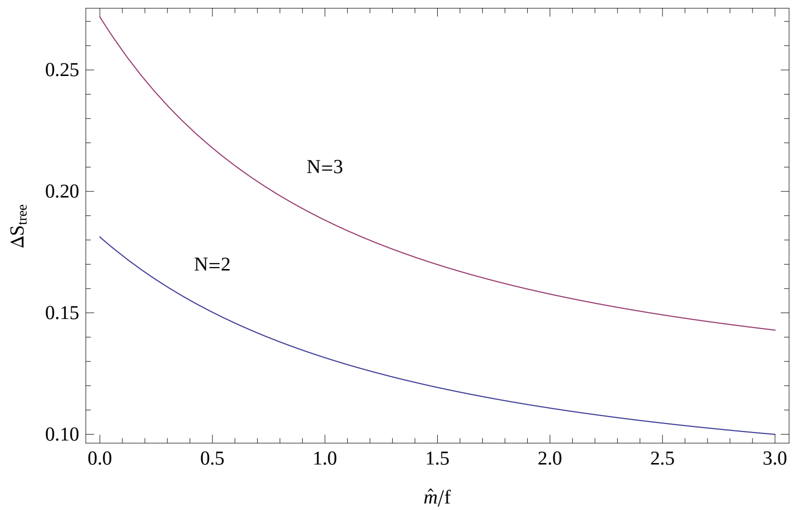
- combining with f_ρ, f_ω, f_ϕ get an approximate extrapolation for quarkonium decay constants over wide range of $\hat{m}$: rescale to BTC via scale factor f/f_π

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

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

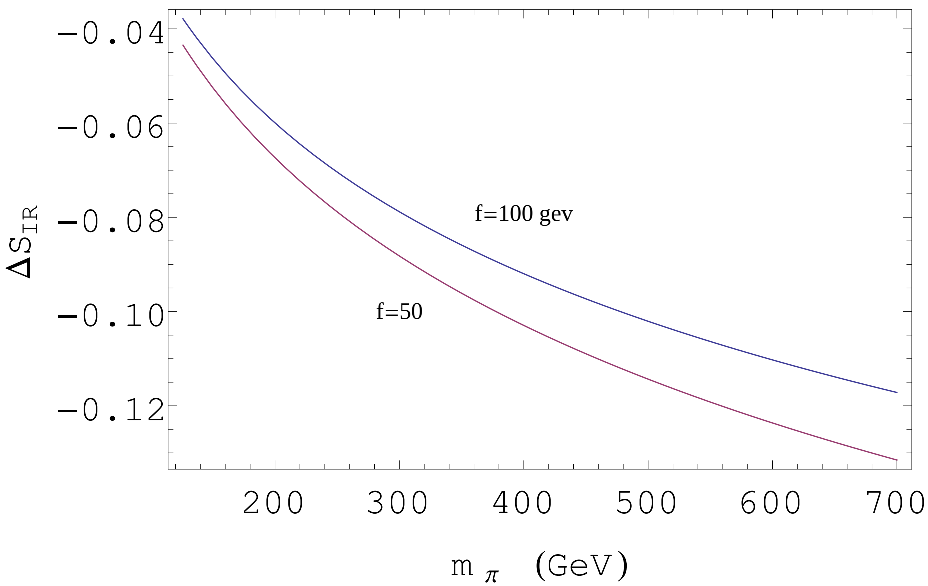
$\mu_V, \mu_A \approx 2.2$ GeV in naive quark model QCD fit.

- taking $f_{a_1} = f_{a_1}^{\rm QCD} \times f/f_\pi^{\rm QCD}$ obtain



ΔS from "low energy" pion, higgs, Z loops

- example: non-susy one Higgs doublet BTC Carone, Simmons; Carone, Georgi (expect similar results in two higgs doublet case, in progress)
- $\Delta S_{\rm IR}$ vs m_π suggests an additional significant decrease in S away from the chiral limit, but for $\hat{m}/f \lesssim 2$, so reasonable to consider pion loop

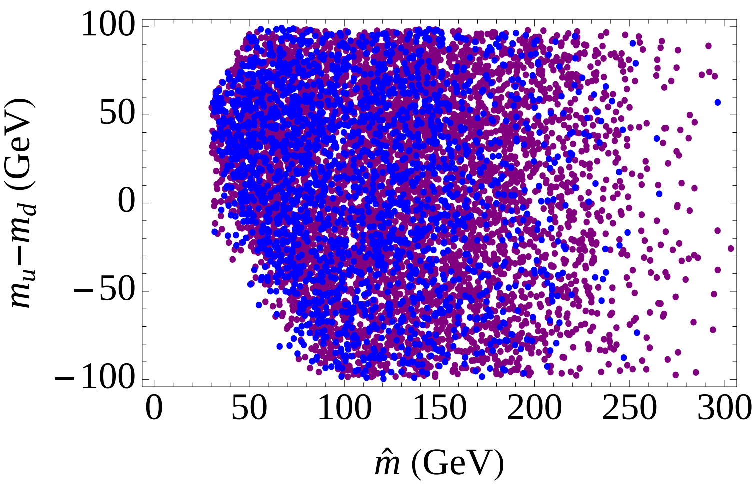


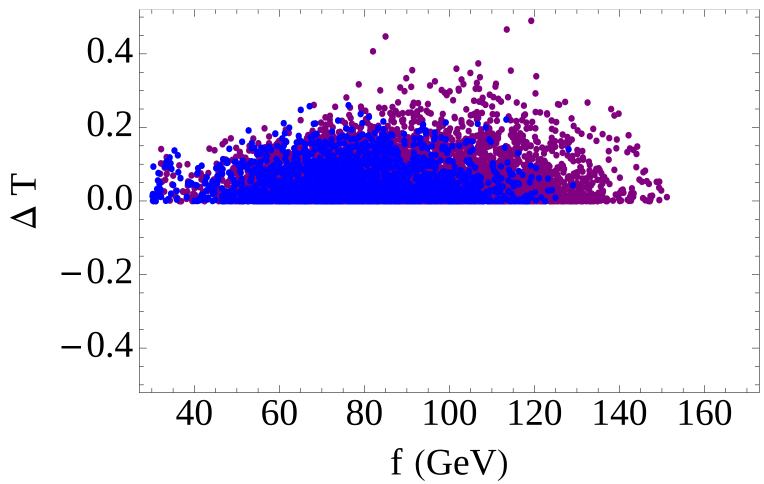
T away from the chiral limit

- $\Delta T_{\rm tree}$ 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 Higgs scans

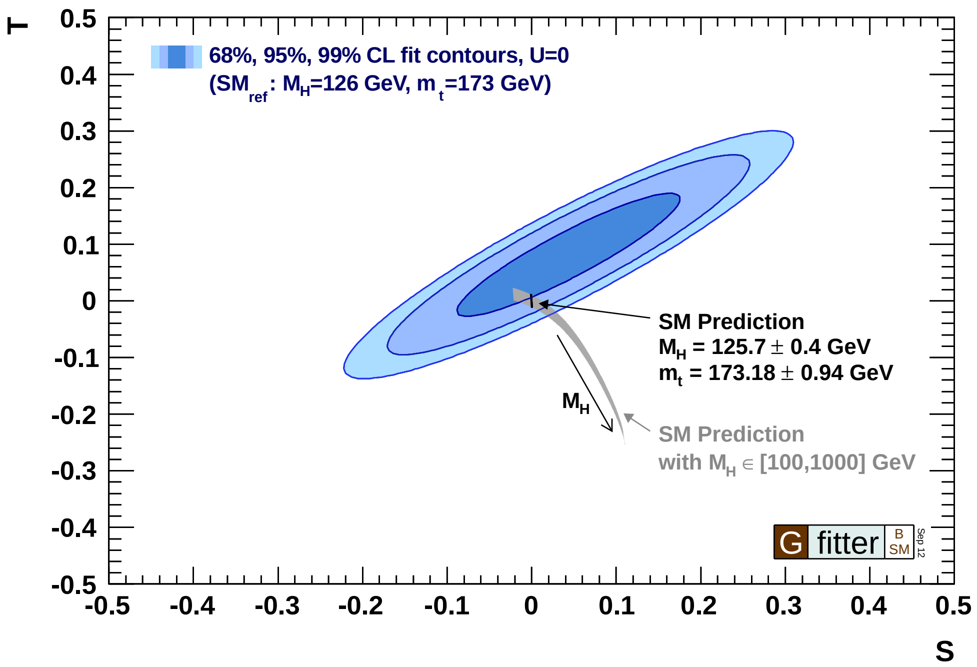
- $\Delta T_{\rm IR}$ due to $\pi^+ - \pi^-$ mass splitting
  - previous authors considered $\pi^+ - \pi^-$ mass splitting via (in our notation)

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

  - 1-loop diagrams with π's, Higgs in loop then yields a scale dependent (log-divergent) contribution to T - interpreted as logarithmic enhancement by setting the scale to $\Lambda_\chi \sim 4\pi f$.
  - thought to dominate over $\Delta T_{\rm tree}$

- instead we attribute the $\pi^+ - \pi^0$ mass splitting 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 the loops, yields finite, negligible $T_{\rm IR} < 0.001$

Summary of S and T



- for $N_{\rm TC} = 2$ can easily lie inside the 1σ ellipse when away from the chiral limit ! Achieved via QCD-like dynamics. No need to speculate about non-QCD like walking or conformal dynamics

  - $\Delta S_{\rm tree} < 0.15$, $\Delta S_{\rm IR} \sim -0.10$ for $\hat{m} \sim f$
  - $\Delta T_{\rm tree} \sim 0.1$ for $|m_U - m_D| \sim 90$ GeV, $\Delta T_{\rm IR}$ is neglgible

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

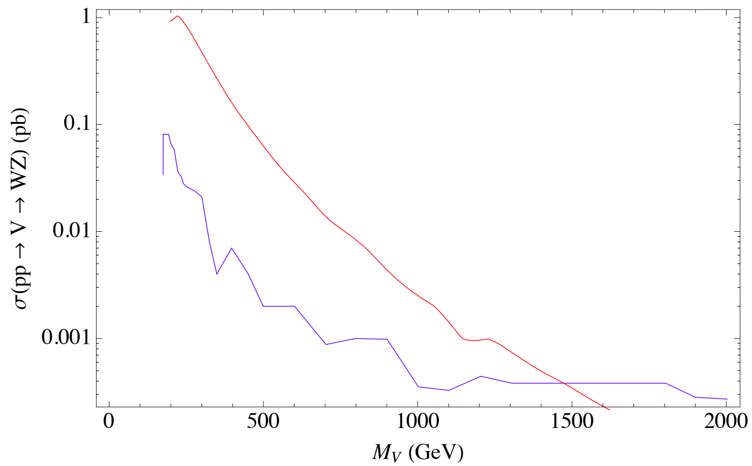
  - CMS presents bounds on $\sigma(pp \to W' \to W^\pm Z)$, together with predictions for the sequential SM W' (SSM) Altarelli et al.

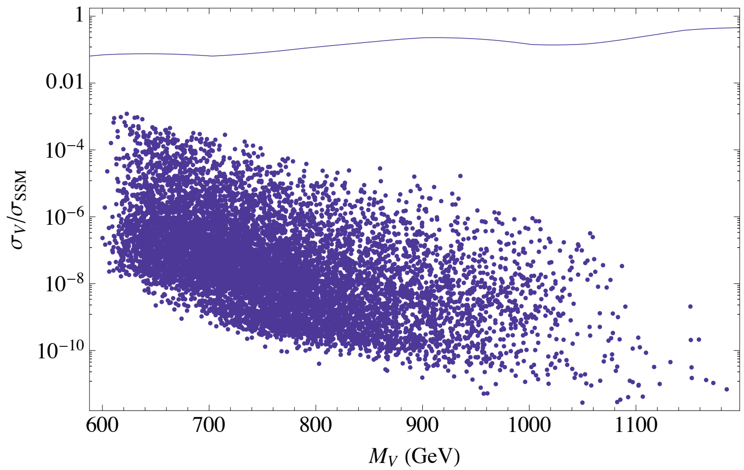
  - SSM $W'ff$ couplings have SM strength;
    $W'WZ$ coupling is SM strength $\times M_W M_Z / M_{W'}^2$

  - obtain the ratio
$$\frac{\sigma(pp \to W' \to WZ)_{\text{bound}}}{\sigma(pp \to W' \to WZ)_{\text{SSM}}}$$

  - compare this to the ratio
$$\frac{\sigma(pp \to \rho \to WZ)}{\sigma(pp \to W' \to WZ)_{\text{SSM}}}$$

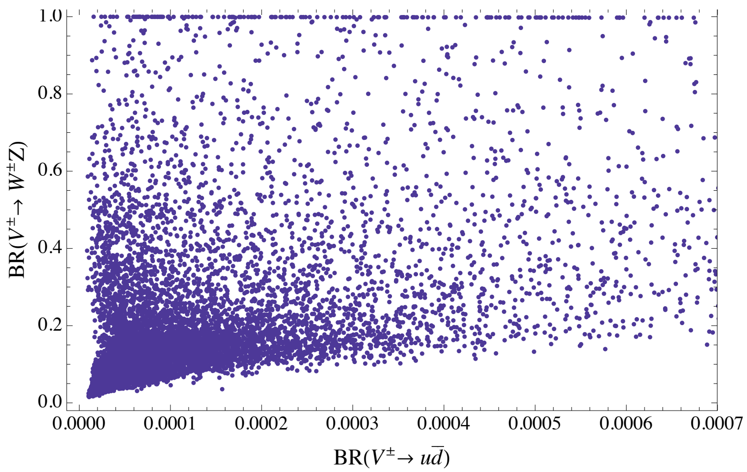
  assuming narrow width approximation for the ρ. Taking into account the ρ width will only weaken the CMS constraint on BTC

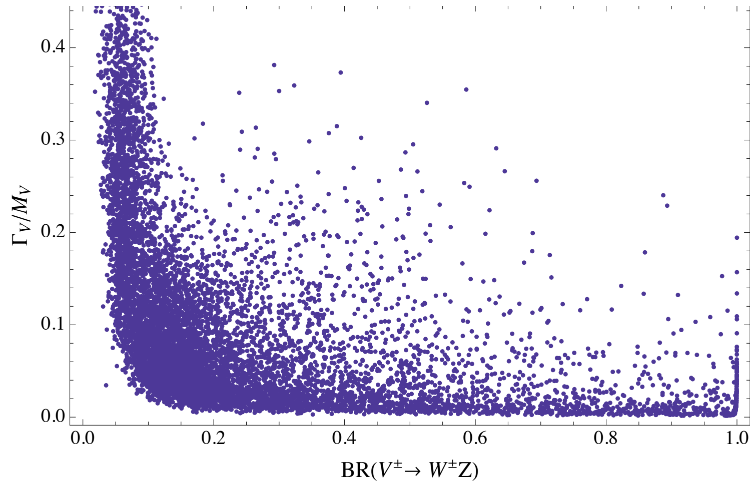




Left: CMS bound (blue) and SSM W' prediction (red); Right: line is ratio of CMS bound to SSM prediction, scatter points are ratio of BTC predictions for NDA scan to SSM prediction

$\Rightarrow$ LHC is not sensitive to Drell-Yam production of TC vectors





- 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 tiny
  - in narrow width approximation

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

- However, sensitivity to ρ in WW scattering could be interesting