E_6 inspired composite Higgs model and 750 GeV diphoton excess

Roman Nevzorov (University of Adelaide & ITEP)

Australian Government
Australian Research Council
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER
THE UNIVERSITY of ADELAIDE
SUB CRUCE LUMEN
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

in collaboration with A.W.Thomas

Outline

- Introduction
- E_6 inspired composite Higgs model and orbifold GUT
- 750 GeV diphoton resonance
- Conclusions

Based on:

R. Nevzorov and A. W. Thomas, arXiv:1605.07313 [hep-ph];

R. Nevzorov and A. W. Thomas, Phys. Rev. D **92** (2015) 075007 [arXiv:1507.02101 [hep-ph]].

Introduction

- The properties of a new scalar particle, observed by the ATLAS and CMS, strongly suggest that it is the SM–like Higgs boson.
- In the SM the Higgs scalar potential is given by
$$V(H) = m_H^2 H^\dagger H + \lambda (H^\dagger H)^2 \,.$$
- The discovery of the BEH boson with $m_h \simeq 125\,\text{GeV}$ allows to estimate the values of parameters
$$m_H^2 \approx -(90\,\text{GeV})^2, \qquad \lambda \approx 0.13\,.$$
- In composite Higgs models so small values of m_H^2 and λ can be obtained if Higgs emerges as a pseudo–Nambu–Goldstone boson (pNGB) from the spontaneous breaking of some global symmetry.
- The composite Higgs models involve weakly–coupled elementary and strongly interacting sectors.

- The sector of weakly–coupled elementary particles includes the SM gauge bosons and SM fermions.
- The strongly interacting sector results in a set of bound states that involves Higgs doublet as well as composite partners of quarks, leptons and gauge bosons.
  - At low energies those states identified with SM fermions (bosons) (ψ^i_a) are a mixture of the corresponding elementary fermionic (bosonic) states ($\tilde{\psi}^i_a$) and their fermionic (bosonic) composite partners ($\tilde{\Psi}^i_a$), i.e.

$$|\psi^i_a >= c^i_a|\tilde{\psi}^i_a > + s^i_a|\tilde{\Psi}^i_a > \,.$$

- The couplings of the SM states to the composite Higgs are determined by the fractions of the compositeness of these states. For up– and down–quarks one gets

$$y^u_{ij} = s^i_q Y^u_{ij} s^j_u \,, \qquad y^d_{ij} = s^i_q Y^d_{ij} s^j_d \,, \qquad i,\, j = 1, 2, 3\,.$$

- The top quark is so heavy that the right–handed top quark (t^c) should have sizeable fraction of compositeness.
- If t^c is entirely composite then the approximate gauge coupling unification can be achieved [K. Agashe, R. Contino, R. Sundrum, Phys. Rev. Lett. **95** (2005) 171804].
- This happens, when all composite states fill in complete $SU(5)$ representations and the set of weakly–coupled elementary states involves

$$(q_i,\, d^c_i,\, \ell_i,\, e^c_i) + u^c_\alpha + \bar{q} + \bar{d^c} + \bar{\ell} + \bar{e^c} + \eta\,, \qquad \alpha = 1, 2\,.$$

- It is expected that the dynamics of the strongly interacting sector leads to the $10 + \overline{5} + 1$ multiplets of $SU(5)$ that get combined with $\bar{q}$, $\bar{d^c}$, $\bar{\ell}$, $\bar{e^c}$ and η forming a set of vector–like states.

- The only exceptions are the components of 10–plet associated with t^c, which survive down to the EW scale.
- In the one–loop approximation the exact gauge coupling unification is attained for $\alpha_3(M_Z) \simeq 0.109$.
- The approximate unification of the SM gauge couplings in such models can take place around the scale $M_X \sim 10^{15} - 10^{16}$ GeV [M. Frigerio, J. Serra, A. Varagnolo, JHEP **1106** (2011) 029; J. Barnard, T. Gherghetta, T. S. Ray, A. Spray, JHEP **1501** (2015) 067].
- Thus it is interesting to consider the embedding of the composite Higgs models into well known GUTs.
- In $N=2$ SUSY GUT based on E_8 all SM particles belong to 248 dimensional representation of E_8 that decomposes under E_6 as follows

$$\mathbf{248} \to \mathbf{78} \oplus 3\times\mathbf{27} \oplus 3\times\overline{\mathbf{27}} \oplus 8\times\mathbf{1}\,.$$

- Currently, the best candidate for the "Theory of Everything", i.e. hypothetical single framework that explains and links together all physical aspects of the universe, is ten–dimensional heterotic superstring theory based on $E_8 \times E'_8$.
- Within superstring theory gauge and gravitational anomaly cancellation, which is necessary for a consistent theory, was found to occur only for the gauge groups $SO(32)$ or $E_8 \otimes E'_8$.
- Compactification of extra dimensions leads to an effective supergravity and results in the breakdown of E_8 to E_6 or its subgroups in the observable sector.
- This stimulates the investigation of the orbifold GUT models based on the $E_6 \otimes G_0$ gauge group.

E$_6$CHM and orbifold GUT

- In the composite Higgs models the appropriate suppression of the baryon number violating operators and the Majorana masses of the left–handed neutrino can be achieved if global $U(1)_B$ and $U(1)_L$ are imposed.
- In the E_6 inspired models almost exact conservation of the $U(1)_B$ and $U(1)_L$ charges may occur if elementary fermions with different baryon or lepton numbers stem from different 27–plets of E_6.
- All other components of these 27–plets have to gain masses of the order of M_X.
- Such a splitting of the E_6 fundamental representations can take place within the six–dimensional orbifold SUSY GUT model based on the $E_6 \times G_0$ gauge group.
- Near the GUT scale M_X the $E_6 \times G_0$ gauge group is broken down to the $SU(3)_C \times SU(2)_W \times U(1)_Y \times G$.

- Gauge groups G_0 and G are associated with the strongly coupled sector.
- Fields from the strongly coupled sector can be charged under both E_6 and G_0 (G) gauge symmetries.
- The weakly–coupled sector involves elementary states that participate in the E_6 interactions only.
- We consider the compactification of two extra dimensions on the orbifold $T^2/(Z_2 \times Z_2^I \times Z_2^{II})$.
- The Z_2, Z_2^I and Z_2^{II} reflection symmetries allow to reduce the physical region to a pillow with the four $4D$ branes located at its corners.
- In this model the elementary quark and lepton fields are components of different bulk 27–plets.

- The components Φ_i and $\overline{\Phi}_i$ of the bulk 27 supermultiplet transform under Z_2, Z_2^I and Z_2^{II} as follows

$$\Phi_i(x,-y,-z) = P_{ii}\Phi_i(x,y,z)\,, \qquad \overline{\Phi}_i(x,-y,-z) = -P_{ii}\overline{\Phi}_i(x,y,z)\,,$$
$$\Phi_i(x,-y',-z) = P^I_{ii}\hat{\Phi}_i(x,y',z)\,, \qquad \overline{\Phi}_i(x,-y',-z) = -P^I_{ii}\overline{\Phi}_i(x,y',z)\,,$$
$$\Phi_i(x,-y,-z') = P^{II}_{ii}\hat{\Phi}_i(x,y,z')\,, \qquad \overline{\Phi}_i(x,-y,-z') = -P^{II}_{ii}\overline{\Phi}_i(x,y,z')\,,$$

where $y' = y - \pi R_5/2$ and $z' = z - \pi R_6/2$.

- The elements of P, P^I and P^{II} can be written in the following form

$$(P)_{ii} = \sigma \exp\{2\pi i \Delta \alpha_i\}\,, \qquad (P^I)_{ii} = \sigma_I \exp\{2\pi i \Delta^I \alpha_i\}\,,$$
$$(P^{II})_{ii} = \sigma_{II} \exp\{2\pi i \Delta^{II} \alpha_i\}\,,$$

where σ, σ_I and σ_{II} are parities of the bulk 27 supermultiplet, i.e. $\sigma, \sigma_I, \sigma_{II} \in \{+,-\}$; α_j are E_6 weights while Δ, Δ^I and Δ^{II} are gauge shifts.

- We choose the following gauge shifts

$$\Delta = \left(0,\, 0,\, 0,\, \frac{1}{2},\, 0,\, 0\right), \qquad \Delta^I = \left(\frac{1}{2},\, \frac{1}{2},\, \frac{1}{2},\, \frac{1}{2},\, \frac{1}{2},\, 0\right),$$
$$\Delta^{II} = \left(\frac{1}{2},\, \frac{1}{2},\, \frac{1}{2},\, 0,\, \frac{1}{2},\, 0\right),$$

that correspond to the orbifold parity assignments shown in the Table.

Orbifold parity assignments in the bulk $27'$ supermultiplet with $\sigma = \sigma_I = \sigma_{II} = +1$.

	q	d^c	u^c	ℓ	e^c	ν^c	h^u	h^d	h	h^c	s
Z_2	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$	$-$
Z_2^I	$-$	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$+$	$+$	$+$
Z_2^{II}	$-$	$-$	$+$	$+$	$+$	$-$	$-$	$+$	$+$	$-$	$-$

- On the branes O, O_I and O_{II} the E_6 gauge group is broken down to $SU(6) \times SU(2)_N$, $SU(6)' \times SU(2)_W$ and $SO(10)' \times U(1)'$ respectively.
- All fields from the strongly coupled sector are confined on the brane O, where E_6 symmetry is broken down to the $SU(6) \times SU(2)_N$ subgroup.
- The unbroken gauge group of the effective $4D$ theory is $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ which is the intersection of the E_6 subgroups at the fixed points.
- The scalar components of the supremultiplets localised on the branes O_I and O_{II} can be used to break $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ down to the SM gauge group so that $SU(6)$ symmetry remains intact.
- The SM gauge interactions break $SU(6)$ symmetry.

- Nonetheless, if the gauge couplings of G are considerably larger than the SM gauge couplings, then $SU(6)$ can be still an approximate global symmetry of the composite sector at low energies.
- Thus the strongly interacting sector in the E_6 inspired composite Higgs model (E_6CHM) possesses $SU(6)\times U(1)_B\times U(1)_L$ global symmetry.
- In the E_6CHM the lightest exotic fermion state, that do not participate in the SM gauge interactions, may be stable because of the conservation of baryon number/baryon triality

$$\Psi \longrightarrow e^{2\pi i B_3/3}\Psi\,, \qquad B_3=(3B-n_C)_{\text{mod }3}\,,$$

where n_C is the number of colour indices ($n_C=1$ for the colour triplet and $n_C=-1$ for $\overline{\mathbf{3}}$).

- Near the scale $f \gtrsim 10\,$TeV the $SU(6)$ global symmetry is broken down to its $SU(5)$ subgroup, that contains the SM gauge group.
- The $SU(6)/SU(5)$ coset space involves eleven pNGB states.
- One of these pNGB states ϕ_0 does not participate in the SM gauge interactions.
- Ten others form the SM–like Higgs doublet H and the $SU(3)_C$ triplet T.
- These pNGB states do not carry any baryon and/or lepton numbers.
- Since in the E_6CHM $f \gtrsim 10\,$TeV, a significant tuning, $\sim 0.01\%$, is needed to get the SM–like Higgs with mass $125\,$GeV.

750 GeV diphoton resonance

- In the E_6CHM ϕ_0 can be identified with the state which results in the excess of diphoton events at an invariant mass around $750\,\text{GeV}$.
- It is important that no resonance with mass $750\,\text{GeV}$ has been detected in any other channels including $pp \to t\bar{t}, WW, ZZ, b\bar{b}, \tau\bar{\tau}$ and jj.
- The state ϕ_0 could potentially mix with the Higgs boson which would give rise to large partial decay widths of the $750\,\text{GeV}$ resonance to ZZ, WW and $t\bar{t}$,
- Here invariance under CP transformation is imposed.
- In this case ϕ_0 manifests itself in the Yukawa interactions with fermions as a pseudoscalar field.
- Therefore ϕ_0 can not mix with the Higgs boson because of the almost exact CP–conservation.

- The Lagrangian that describes the interactions between $\phi_0 = A$ and other states can be written as

$$\mathcal{L}_A = A(i\kappa_D \bar{d}^c D^c + i\kappa_Q \bar{q} Q + i\lambda_L \bar{\ell} L + i\lambda_E \bar{e^c} E^c + i\lambda_\eta \bar{\eta}\eta + h.c.) + \frac{\alpha_Y}{16\pi\Lambda_1} A B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{\alpha_2}{16\pi\Lambda_2} A W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + \frac{\alpha_3}{16\pi\Lambda_3} A G^\sigma_{\mu\nu}\widetilde{G}^{\sigma\mu\nu} + \frac{y_t}{\Lambda_t} A(i\bar{t}_L H^0 t_R + h.c.) + \frac{y_b}{\Lambda_b} A(i\bar{b}_L H^0 b_R + h.c.) + \ldots .$$

  - Λ_1, Λ_2 and Λ_3 are expected to be of the order of scale f.
  - When t^c belongs to **20** of $SU(6)$, the scale $\Lambda_t = \sqrt{15} f$.
  - If t^c belongs to **15** of $SU(6)$ then $\Lambda_t = \sqrt{\frac{60}{49}} f$.
- The mass terms of exotic fermions are given by

$$\mathcal{L}_{mass} = \mu_D \bar{d}^c D^c + \mu_Q \bar{q} Q + \mu_L \bar{\ell} L + \mu_E \bar{e^c} E^c + \mu_\eta \bar{\eta}\eta + h.c. .$$

- Here we assume that $\mu_D, \mu_Q,\ \mu_L$ and μ_E are larger than $375\,$GeV.

- Integrating out the heavy exotic states one gets

$$\mathcal{L}^{A}_{eff} = c_1 A B_{\mu\nu} \widetilde{B}^{\mu\nu} + c_2 A W^{a}_{\mu\nu} \widetilde{W}^{a\mu\nu} + c_3 A G^{\sigma}_{\mu\nu} \widetilde{G}^{\sigma\mu\nu} + \frac{y_t}{\Lambda_t} A (i \bar{t}_L H t_R + h.c.) + i \lambda_\eta A (\bar{\eta}\eta + h.c.) \, .$$

- The effective Lagrangian that describes the interactions of these fields with the electromagnetic one is given by

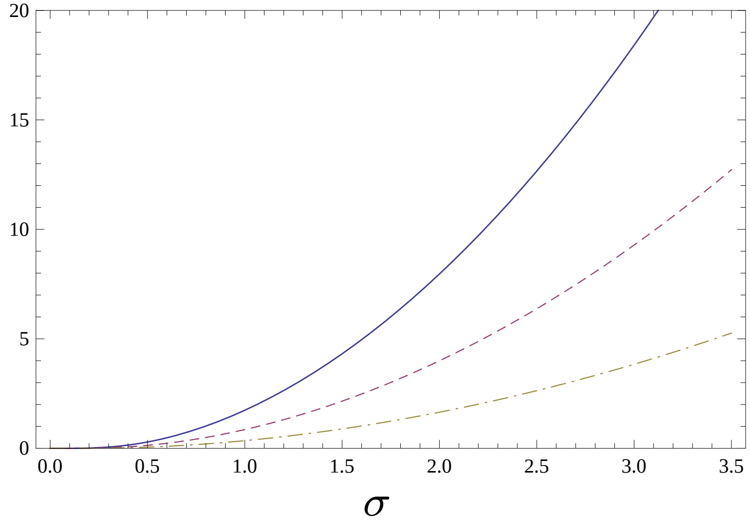
$$\mathcal{L}^{A\gamma\gamma}_{eff} = c_\gamma A F_{\mu\nu} \widetilde{F}^{\mu\nu} \, , \qquad c_\gamma = c_1 \cos^2\theta_W + c_2 \sin^2\theta_W \, .$$

- At the LHC the SM singlet pNGB state A is predominantly produced through gluon fusion.
- Then the diphoton production cross section can be approximately estimated as

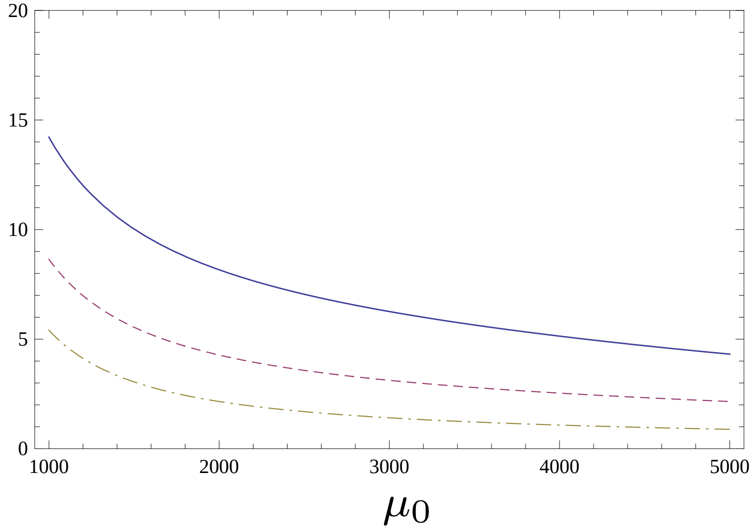
$$\sigma_{\gamma\gamma} = \sigma_{gg} \frac{\Gamma(A \to \gamma\gamma)}{\Gamma_A} \simeq 7.3\,\text{fb} \times \left(\frac{\Gamma(A \to gg)\,\Gamma(A \to \gamma\gamma)}{\Gamma_A\, m_A} \times 10^6 \right) .$$

- If $\mu_\eta > 375\,$GeV then the total decay width $\Gamma_A \simeq \Gamma(A \to gg)$ tends to be small, $\Gamma_A/m_A \lesssim 10^{-4}$.
- We focus on the scenario with $\mu_D = \mu_Q = \mu_L = \mu_0 \gtrsim \mu_E$, $\mu_E = 400\,$GeV$, 500\,$GeV and 800 GeV as well as $\kappa_D = \kappa_Q = \lambda_L = \lambda_E = \sigma \simeq 1.5$.
- We also set $\Lambda_t \simeq 80\,$TeV$(f \simeq 20\,$TeV$)$ to achieve the appropriate suppression of the decay rate $A \to t\bar{t}$.
- The value of μ_0 should be sufficiently small ($\ll 10\,$TeV) so that reasonably large LHC production cross section of A can be obtained.
- The diphoton production cross section decreases rapidly with increasing μ_E.
- When $\mu_0 \gg \mu_E \simeq 400 - 500\,$GeV the decay rates for $A \to t\bar{t}, WW, ZZ$ and $Z\gamma$ are rather suppressed that may explain why these decays have not been observed yet.

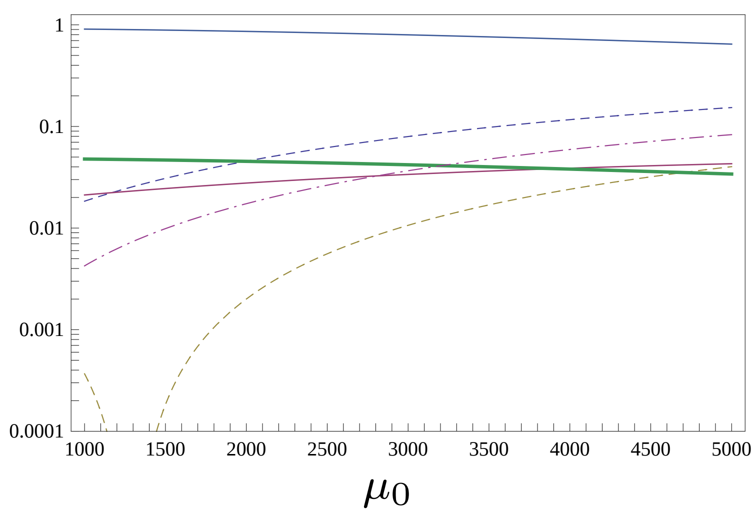
$\sigma(pp \to A \to \gamma\gamma)$[fb]



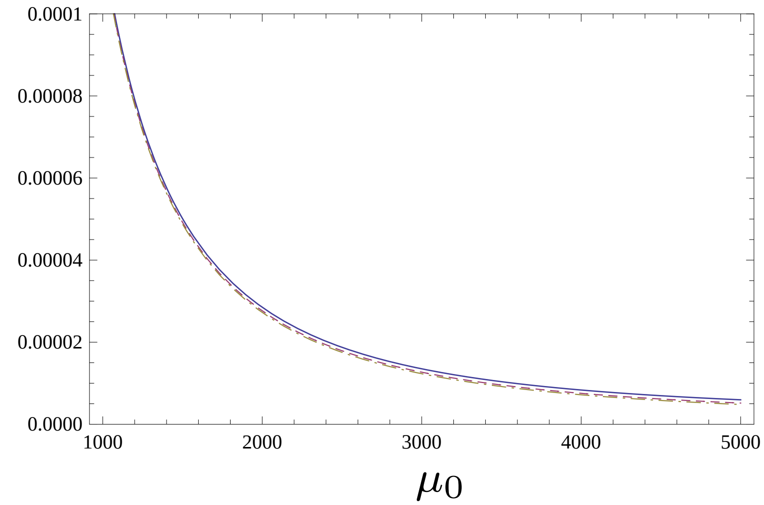
$\sigma(pp \to A \to \gamma\gamma)$[fb]



BR$(A \to t\bar{t}, gg, \gamma\gamma, WW, ZZ, \gamma Z)$



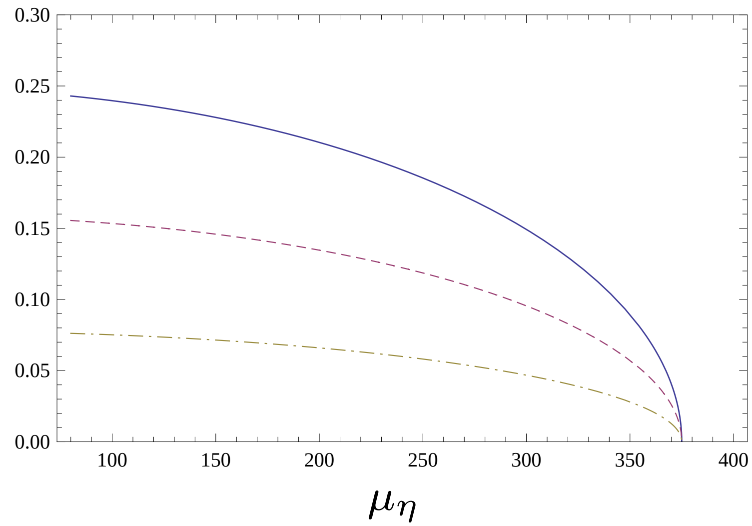
Γ_A/m_A



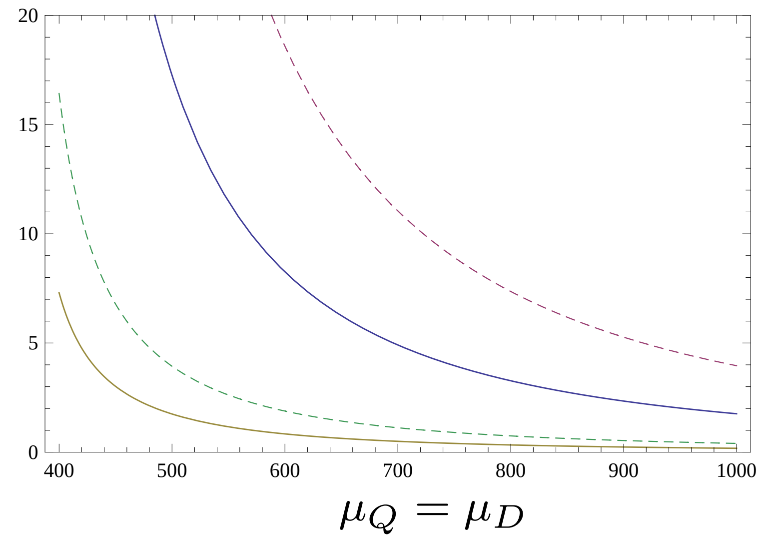
- The pseudoscalar A mainly decays into a pair of gluons that might be difficult to detect if the LHC production cross section of A remains rather small.
- When $\mu_0 \gg \mu_E$ the branching fraction associated with $A \to \gamma\gamma$ is the second largest one.
- $\mathrm{BR}(A \to \gamma\gamma)$ decreases whereas $\mathrm{BR}(A \to ZZ)$ and $\mathrm{BR}(A \to WW)$ increases with decreasing μ_0.
- When μ_0 is around $1\,\mathrm{TeV}$ the values of $\mathrm{BR}(A \to ZZ)$ and $\mathrm{BR}(A \to WW)$ are a few times bigger than $\mathrm{BR}(A \to \gamma\gamma)$.
- Nevertheless the experimental detection of $A \to WW$ and $A \to ZZ$ is more problematic because the W and Z decay mainly into quarks.
- In this case $\mathrm{BR}(A \to t\bar{t})$ and $\mathrm{BR}(A \to \gamma Z)$ are considerably smaller than $\mathrm{BR}(A \to \gamma\gamma)$.

- If $\mu_\eta \lesssim 375$ GeV then the decays of A into $\eta\,\bar{\eta}$ are kinematically allowed.
- As a result λ_η and μ_η can be always adjusted so that $\Gamma_A \simeq 45$ GeV ($\Gamma_A/m_A \simeq 0.06$) or even larger.
- For so large Γ_A the value of $\sigma(pp \to A \to \gamma\gamma) \simeq 5-10$ fb can be obtained only if the masses of all charged exotic fermions are rather close to 375 GeV.
- Here we set $\kappa_D = \kappa_Q = \lambda_L = \lambda_E = \sigma$, $\mu_Q = \mu_D$, $\mu_L = \mu_E = 400$ GeV and consider scenarios with $\sigma = \sqrt{4\pi}$ and $\sigma = 2$ for $\Gamma_A = 45$ GeV and $\Gamma_A = 20$ GeV.
- If Γ_A is 20 GeV or smaller $\sigma(pp \to A \to \gamma\gamma) \simeq 4-5$ fb can be obtained provided the masses of exotic coloured fermions are around 1 TeV or smaller.

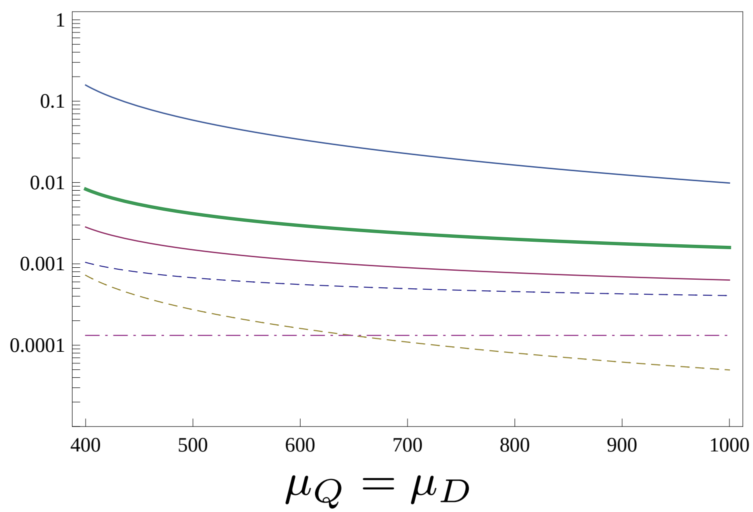
$\Gamma(A \to \eta\bar{\eta})/m_A$



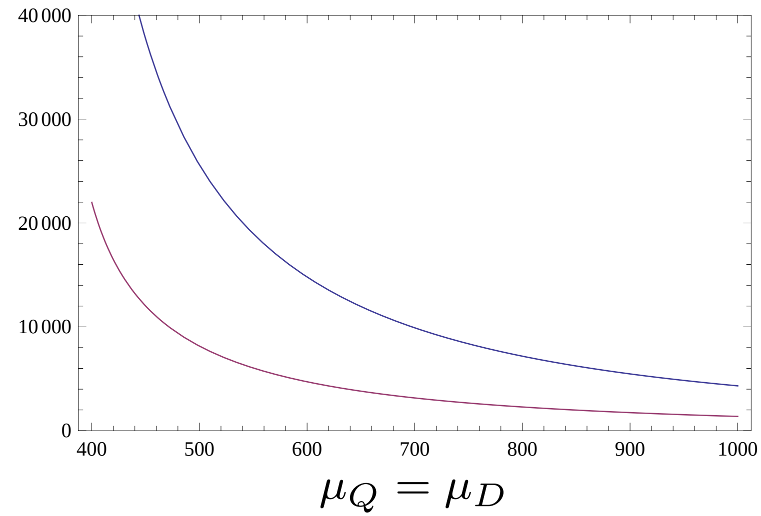
$\sigma(pp \to A \to \gamma\gamma)$[fb]



BR$(A \to gg, WW, ZZ, \gamma\gamma, \gamma Z, t\bar{t})$



$\sigma(pp \to A + X)$[fb]



- In general this scenario leads to quite a large cross section of the process $pp \to j + E_T^{miss}$.
- Moreover, the branching ratios of decays $A \to gg, WW, ZZ$ are considerably larger than the one associated with $A \to \gamma\gamma$.
- The observation of these decay modes should be possible in Run 2 at the LHC.
- The exotic coloured fermions with TeV scale masses are doubly produced.
- Assuming that such states couple most strongly to the third generation fermions, they decay into a pair of third generation quarks and the lightest neutral exotic state resulting in the enhancement of the cross sections for

$$pp \to t\bar{t}b\bar{b} + E_T^{miss} + X\,, \qquad pp \to b\bar{b}b\bar{b} + E_T^{miss} + X\,.$$

Conclusions

- In the E_6CHM the strongly interacting sector possesses an $SU(6) \times U(1)_B \times U(1)_L$ global symmetry.
- Near scale $f \gtrsim 10$ TeV the $SU(6)$ global symmetry is broken down to its $SU(5)$ subgroup, that contains the SM gauge group, resulting in a set of pNGBs states.
- This set, in particular, involves the SM–like Higgs doublet and a pseudoscalar A.
- The interactions of A with exotic matter, which ensures anomaly cancellation and approximate gauge coupling unification, induce couplings of A to gauge bosons.
- As a result, the pseudoscalar A can be identified with the 750 GeV diphoton resonance.
- Such an interpretation requires that either all or some of the exotic states have masses below 1 TeV.