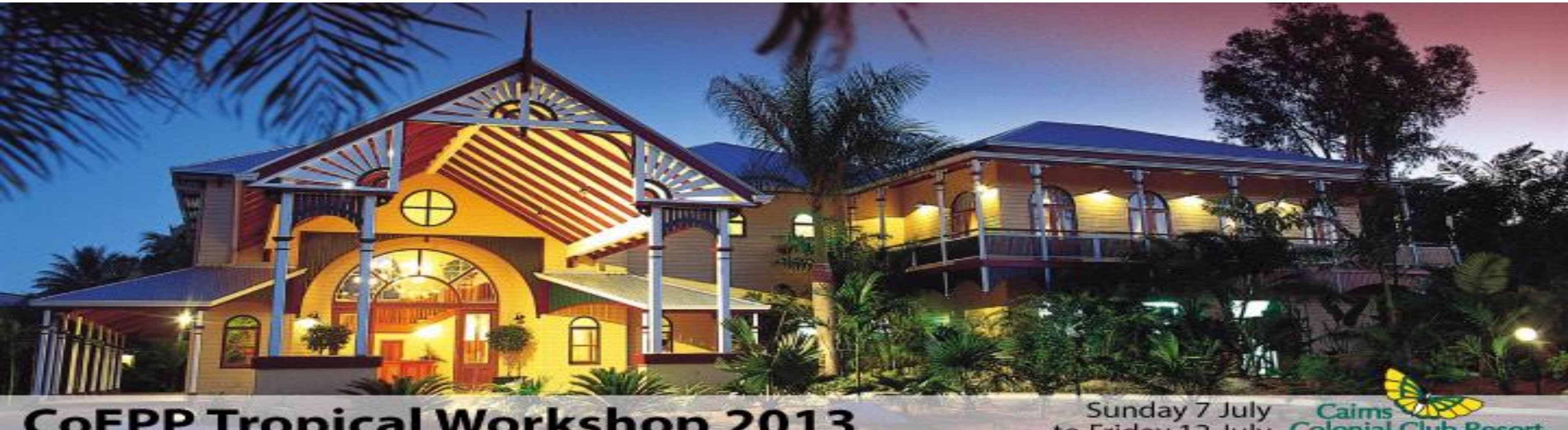
Higgs Physics and Naturalness

Archil Kobakhidze

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

THE UNIVERSITY OF SYDNEY



Discovery of a Higgs boson

- Discovery of a new particle with 134 X heavier than proton has been announced by ATLAS and CMS on 4th of July 2012

- Subsequent measurements of properties (couplings, spin) of this new particle showed that it is some sort of Higgs boson

- This is one of the major scientific discoveries with important implications for our understanding of the origin of mass in the universe

Outline

- What makes a Higgs a Higgs?
  - Gauge invariance
  - Perturbative unitarity
- Properties of the 125-126 GeV LHC resonance
  - Couplings
  - Spin/parity
  - Heavy resonances
- If it's the Higgs boson...
  - Vacuum stability
  - Higgs inflation
- Naturalness
- Conclusions

What makes a Higgs a Higgs?

- Standard Model is an extremely successful theory in describing elementary particles (quarks and leptons) and their electromagnetic, week and strong interactions.
- An important theoretical input is gauge invariance – the only known way to describe interacting force-career (spin 1) quantum fields – gluons, photon and W/Z.

- Consider a free (linearized) massless vector field $A_\mu(x)$

$$\mathcal{L}_A = -\frac{1}{2}\partial_\mu A_\nu \left[\partial^\mu A^\nu - c\,\partial^\nu A^\mu\right]$$

- Canonical variables: $A_\mu(x)\,,\quad \pi^\mu(x) = -\partial^0 A^\mu + c\,\partial^\mu A^0$
- Hamiltonian density:

$$\mathcal{H} = \frac{1}{2}\pi_i^2 + \left(\partial_i A_j - \partial_j A_i\right)^2 - \frac{1}{2}\pi_0^2 + \frac{c(c-1)}{2}\left(\partial_0 A_0\right)^2 + \frac{1-c}{2}\left(\partial_i A_j\right)^2$$

$$\mathcal{H} \geq 0 \longrightarrow c = 1 \longrightarrow \mathcal{H} = \frac{1}{2}\left(E_i^2 + B_i^2\right)$$

- Redundancy in the description (gauge invariance)

$$A'_\mu = A_\mu + \frac{1}{g}\partial_\mu \alpha(x)$$

What makes a Higgs a Higgs?

- Quantisation: $\left[\hat{A}_\mu(x),\ \hat{\pi}_\nu(x')\right]\Big|_{t=t'} = -i\hbar\ \eta_{\mu\nu}\ \delta^3(\vec{x}' - \vec{x})$
- $\hat{A}_0(x),\ \hat{\pi}_0(x)$ -- describe "inverted" oscillators --> negative norm states
- Consistent quantum theory of vector (tensor) fields requires gauge invariance!
- Potential problem: mass term violates gauge invariance (massive W/Z bosons)

$$\mathcal{L}_{m_A} = \frac{1}{2} m_A^2\ A_\mu A^\mu$$

$$\delta\mathcal{L}_{m_A} = m_A^2\ A_\mu \frac{1}{g}\partial^\mu\alpha \neq 0$$

What makes a Higgs a Higgs?

- Nonlinear realisation $$\mathcal{L}_{m_A}^{\rm NLR} = \frac{1}{2} m_A^2 \left(A_\mu - \frac{1}{g}\partial_\mu \theta\right)^2$$

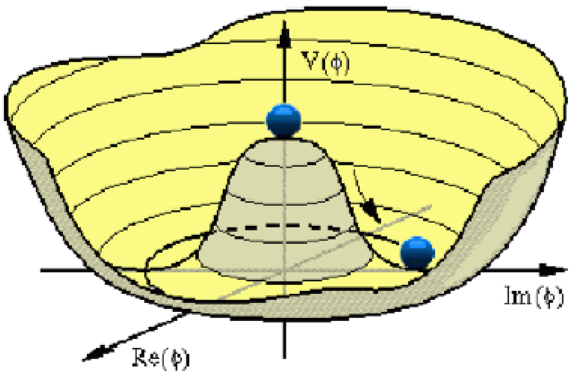
$$\delta\theta = \alpha \to \delta\mathcal{L}_{m_A}^{\rm NLR} = 0$$

- Higgs mechanism $$\Phi = \frac{\rho(x)}{\sqrt{2}} {\rm e}^{i\theta(x)}$$

$$\mathcal{L}_{\rm H} = (D\Phi)^\dagger (D\Phi) - V(\Phi^\dagger \Phi) =$$

$$\frac{1}{2}(\partial_\mu \rho)^2 + \frac{g^2\rho^2}{2}\left(A_\mu - \frac{1}{g}\partial_\mu\theta\right)^2 = \ldots + \frac{g^2}{2}\left(v + 2vh(x) + h^2(x)\right) A_\mu A^\mu + \ldots$$

$$\rho(x) = v + h(x)\ , \quad \langle 0|\rho|0\rangle = v$$



Anderson – 1962 (nonrelativistic)
Higgs; Brout & Englert; Guralnik, Hagen, Kibble –1964
Weinberg – 1968 (Standard Model)
Ellis, Gaillard, Nanopoulos – 1975 (pheno)

What makes a Higgs a Higgs?

SU(3) × SU(2) × U(1)

Linear realisation – All particles are massless.

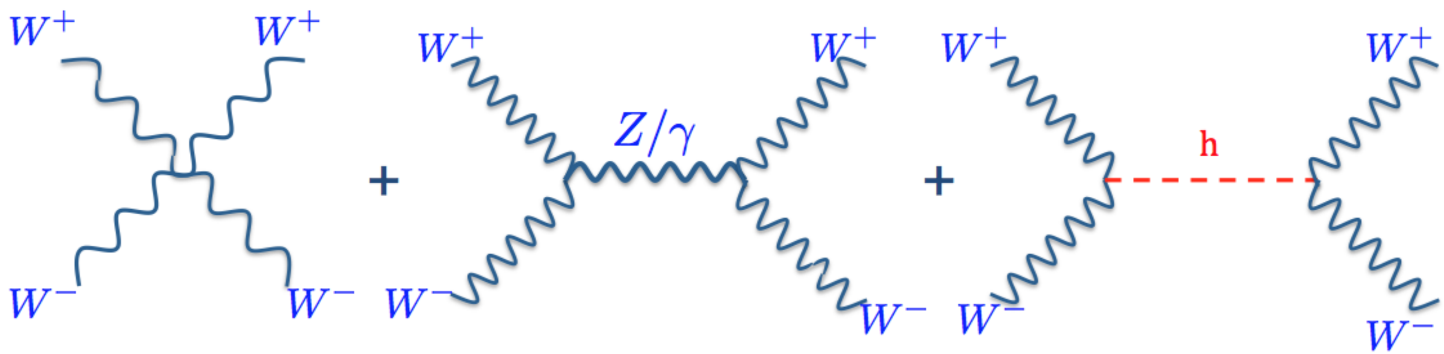
Non-linear realisation – *A priory*, SM particles have arbitrary masses

Higgs mechanism – Masses ~ Higgs interaction strengths, predicts spin 0 boson(s)

Higgs coupling measurements are important!

What makes a Higgs a Higgs?

- Higgs mechanism of spontaneous electroweak symmetry breaking and mass generation automatically ensures perturbative unitarity of processes involving massive electroweak gauge bosons, W/Z.
- Higgs W/Z couplings. Consider WW –> WW scattering:

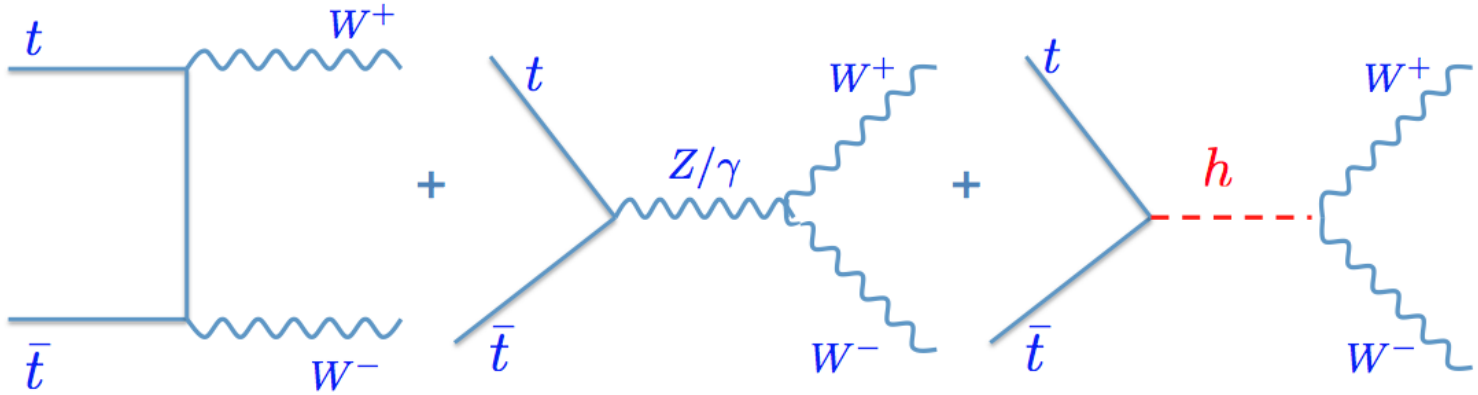


$$\mathcal{A}(WW \to WW) = \mathcal{A}_4 \frac{E^4}{v_{\rm EW}^4} + \mathcal{A}_2 \frac{E^2}{v_{\rm EW}^2} + \mathcal{A}_0 + \mathcal{O}(v_{\rm EW}^2/E^2)$$

- $\mathcal{A}_4 = 0$ - due to the gauge invariance!
- No Higgs: perturbative unitarity is violated at $E_* \approx (4\pi)^{1/2} v_{\rm EW} \sim 900\ {\rm GeV}$
- $\mathcal{A}_2 = 0$ - due to the Higgs mechanism!

What makes a Higgs a Higgs?

- Higgs-fermion couplings. Consider $t\bar{t} \to WW$ scattering:



$$\mathcal{A}(t\bar{t} \to WW) = \mathcal{B}_2 \frac{E^2}{v_{\rm EW}^2} + \mathcal{B}_1 \frac{E}{v_{\rm EW}} + \mathcal{B}_0 + \mathcal{O}(v_{\rm EW}/E)$$

- $\mathcal{B}_2 = 0$ - due to the gauge invariance!

- No Higgs-top coupling: $E_* \approx 16\pi^2 v_{\rm EW}^2/m_t \sim 10 \text{ TeV}$ (Appelquist & Chanowitz, 1987)

- $\mathcal{B}_1 = 0$ - due to the Higgs mechanism!

What makes a Higgs a Higgs?

- We would like to know whether the 125-126 GeV particle discovered at LHC is the Higgs boson of spontaneous electroweak symmetry breaking and fermion mass generation

- Note that the Standard Model Higgs boson is a particular and the simplest case of more general Higgs mechanism. Non-Standard Model properties of the resonance will indicate that more field are involved in the electroweak symmetry breaking or/and it is realised in a different way

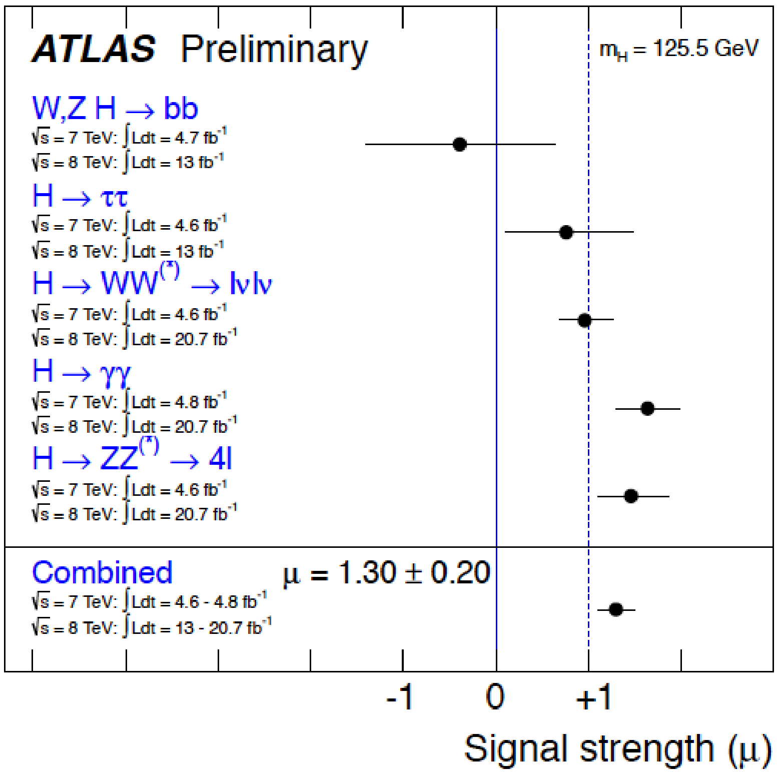
- New particles can manifest in:

  (i) non-standard couplings to photons and gluons (radiative processes);
  (ii) non-standard couplings to fermions;
  (iii) invisible decays

Higgs couplings - 2013

$$m_h = 125.5 \pm 0.2(\text{stat.})^{+0.5}_{-0.6}(\text{syst.})\ \text{GeV}$$

$$m_h = 125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.})\ \text{GeV}$$



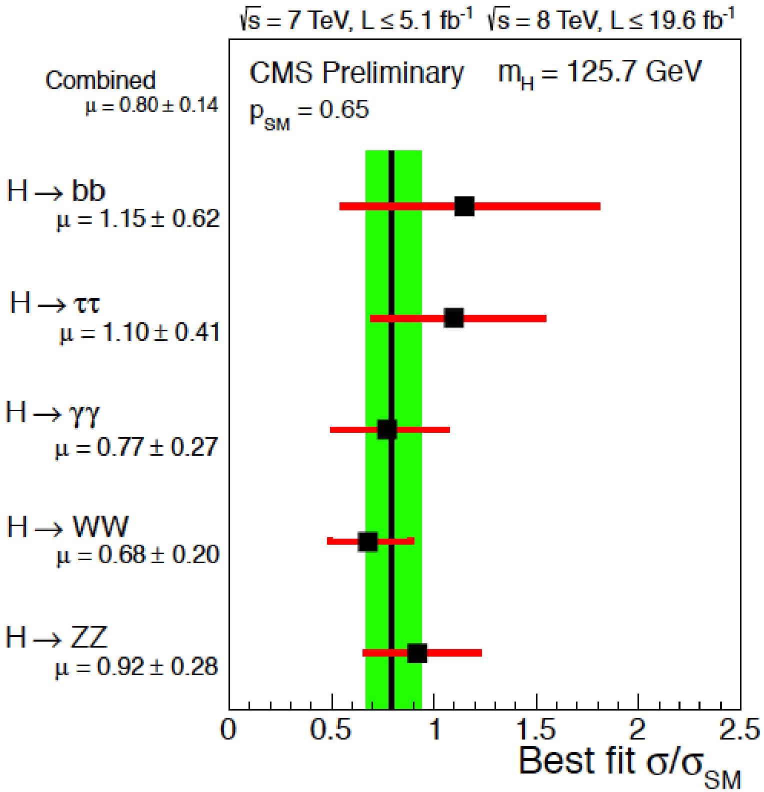
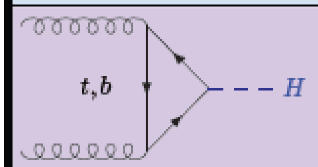
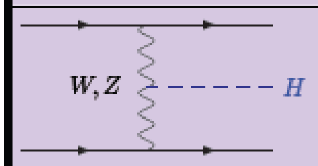
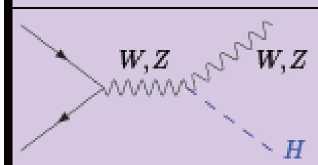
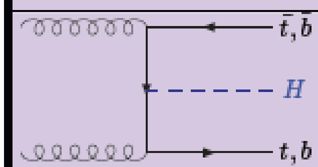


Fig. 1: The signal strength for the individual channel and their combination. The values of μ are given for $M_{\rm H} = 125.5$ GeV for ATLAS and for $M_{\rm H} = 125.7$ GeV for CMS.

Higgs couplings – 2013

	γγ	ZZ	WW	Zγ	gg	bb	ττ
							
							
							
							

done

not yet

difficult

Spin/parity of the resonance

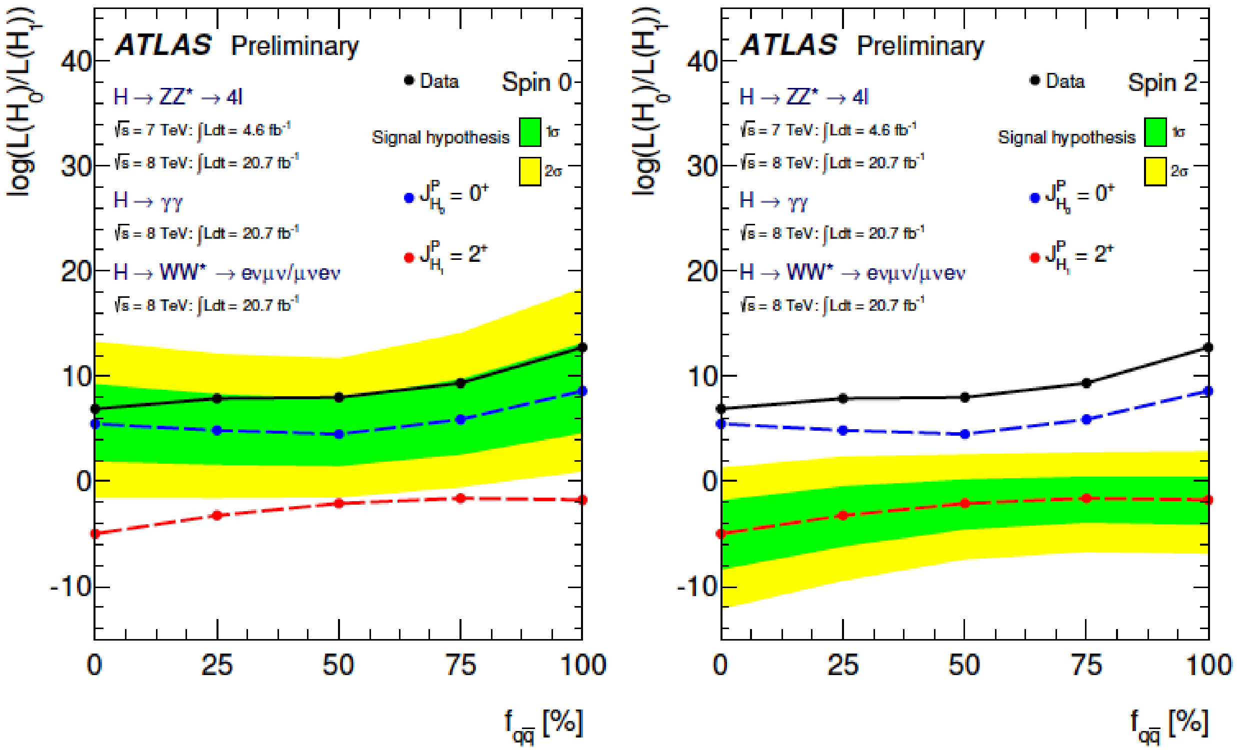
- We know that the resonance is boson, hence spin can be 0,1,2,…
- Spin 1 is excluded due to the observation of $h \to \gamma\gamma$ (Landau-Yang theorem)
- To discriminate between spin 0 and spin 2 we need to study angular distribution of decay products.
- Decay products of spin 0 resonance must be distributed isotropically over 2-sphere, so one expects flat distribution as a function cosθ* (θ* is an angle between of decay products relative to beam axis in the rest frame of decaying particle)
- In contrast, spin 2 decay is not isotropic:

$$\frac{d\sigma}{d\Omega} \sim \frac{1}{4} + \frac{3}{2}\cos^2\theta^* + \frac{1}{4}\cos^4\theta^*$$

- E.g., look at (J. Ellis et al, arXiv:1210.5229)

$$pp \to X_{0,2}(\to \gamma\gamma) + (0,1,2)\ \mathrm{jets}$$

Spin/parity of the resonance

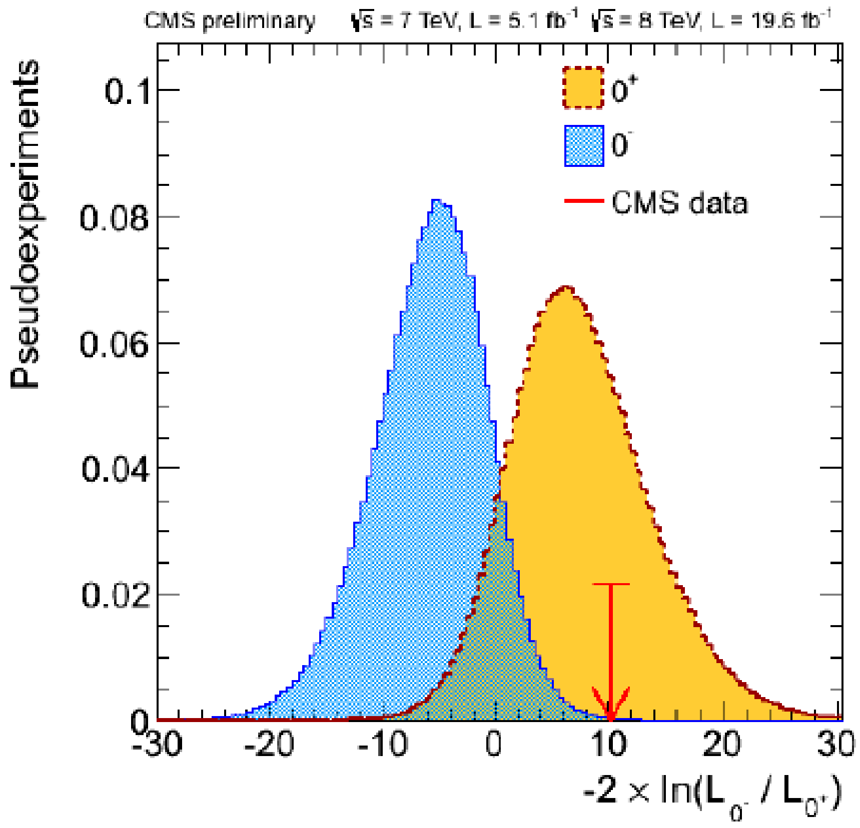


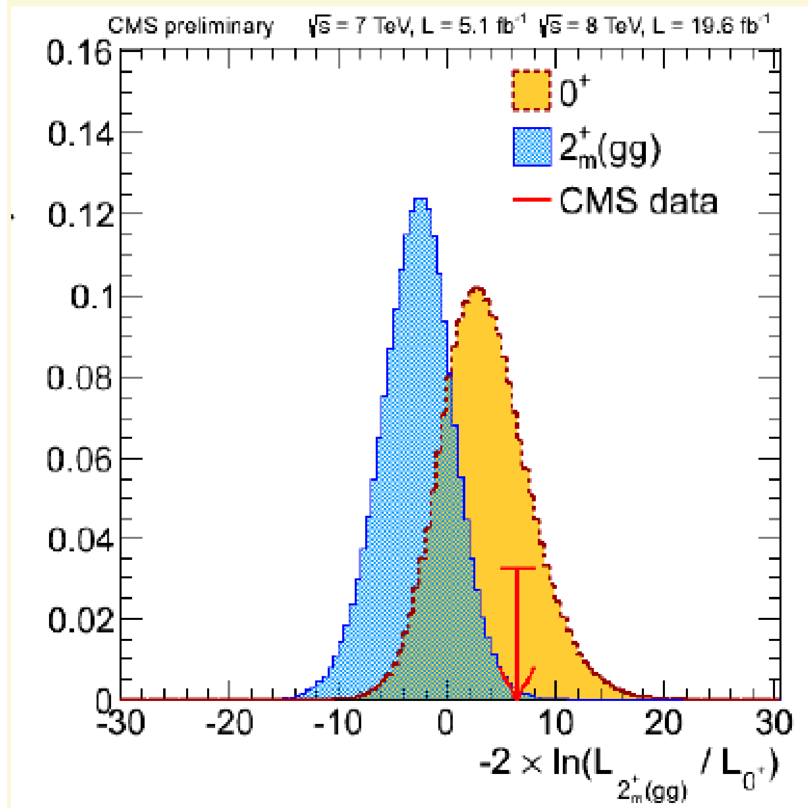
(a) (b)

Figure 2: Expected and observed ratio of profiled likelihoods for the combination of channels as a function of the fraction of the $q\bar{q}$ spin-2 production mechanism. The green and yellow bands represent, respectively, the one and two standard deviation bands for the $J^P = 0^+$ (a) and for the $J^P = 2^+$ (b) hypotheses.

Spin/parity of the resonance

CMS: H->ZZ





CL_s (0^-) : 0.16%

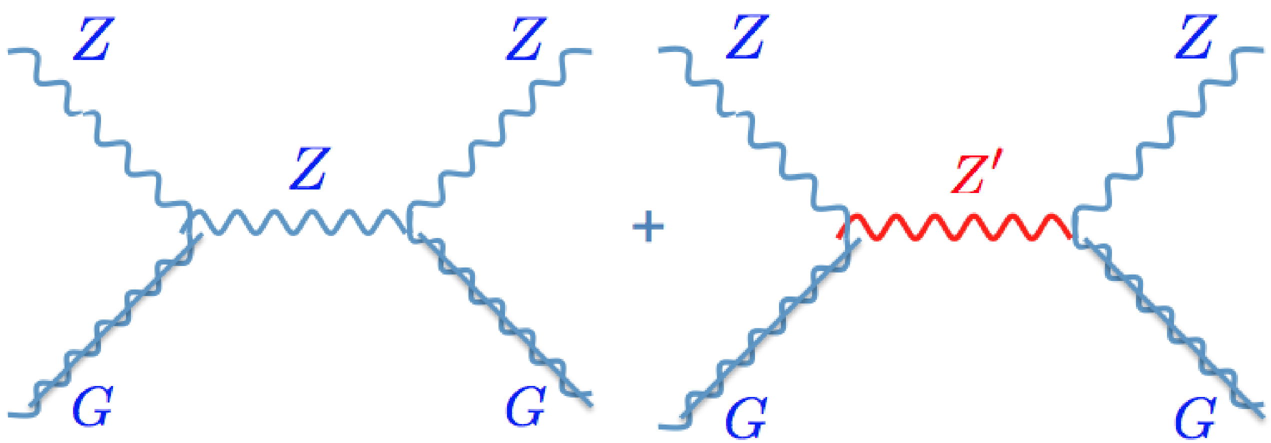
CL_s ($2^+_{m\,gg}$) : 1.5%

Spin/parity and unitarity (A.K., J.Yue, work in progress)

- Linearized effective theory of massive spin-2

$$\mathcal{L}_{int} = -\frac{c_i}{M_{eff}} G^{\mu\nu} T^i_{\mu\nu}\,,\; T^V_{\mu\nu} = -F^\rho_\mu F_{\rho\nu} + (\mu \leftrightarrow \nu) - m_V^2 V_\mu V_\nu$$

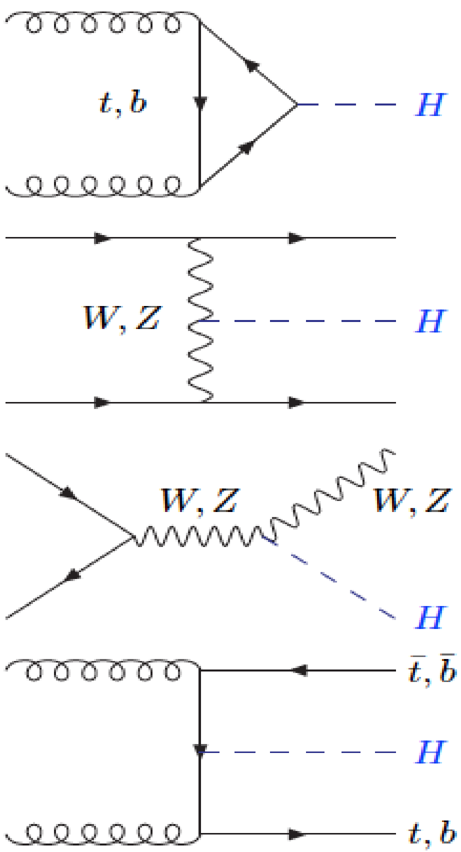
- Consider GZ -> GZ scattering:

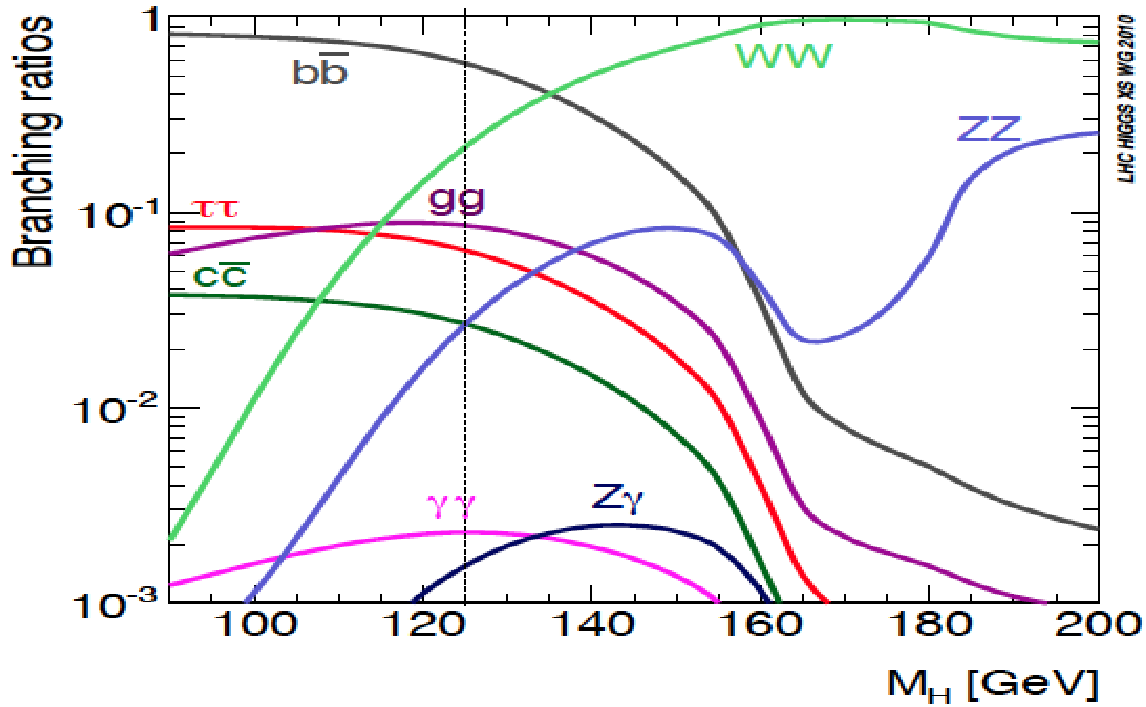


- Perturbative unitarity is violated at $E_* \approx (4\pi)^{1/6} \left(m_h^4 v_{\rm EW}^2\right)^{1/6} \sim 300~{\rm GeV}$
- Properties of *Z'* resonance can be extracted from K-matrix formalism and confronted with experiments

The Standard Model Higgs with m_h=125-126 GeV

- The Standard Model Higgs mass in the range 125-126 GeV is extremely favourable for experimentalists,





…but it's a pain in the neck for theoretists!

Vacuum stability

- The Standard Model vacuum state $|0\rangle_{EW}$

$$ {}_{EW}\langle 0|h|0\rangle_{EW} = v_{EW} \approx 246 \text{ GeV} $$

is a false (local) vacuum. The true vacuum state

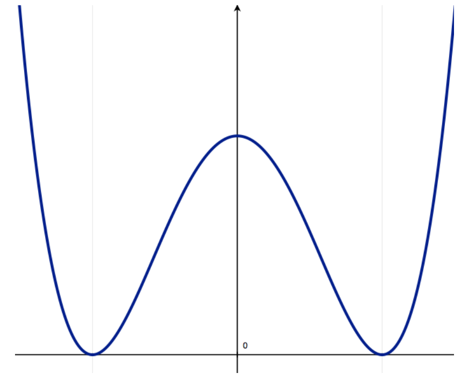
$$ \langle 0|h|0\rangle \sim M_P \approx 10^{18}\text{GeV} \ , $$

and it carries large negative energy density ~ - $(M_P)^4$.

- How long does the electroweak vacuum live?

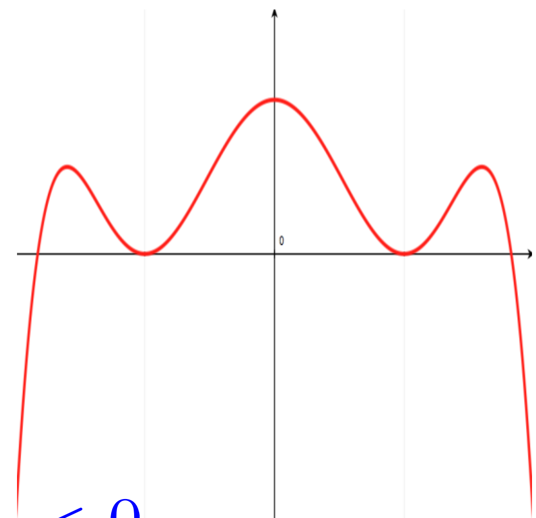
EW vacuum lifetime: flat spacetime estimate

- Electroweak Higgs doublet (in the unitary gauge): $H = \begin{pmatrix} 0 \\ h(x)/\sqrt{2} \end{pmatrix}$



$$V_{\rm H}^{(0)}(h) = \frac{\lambda}{8}\left(h^2 - v_{EW}\right)^2$$

- Effective (quantum-corrected) potential



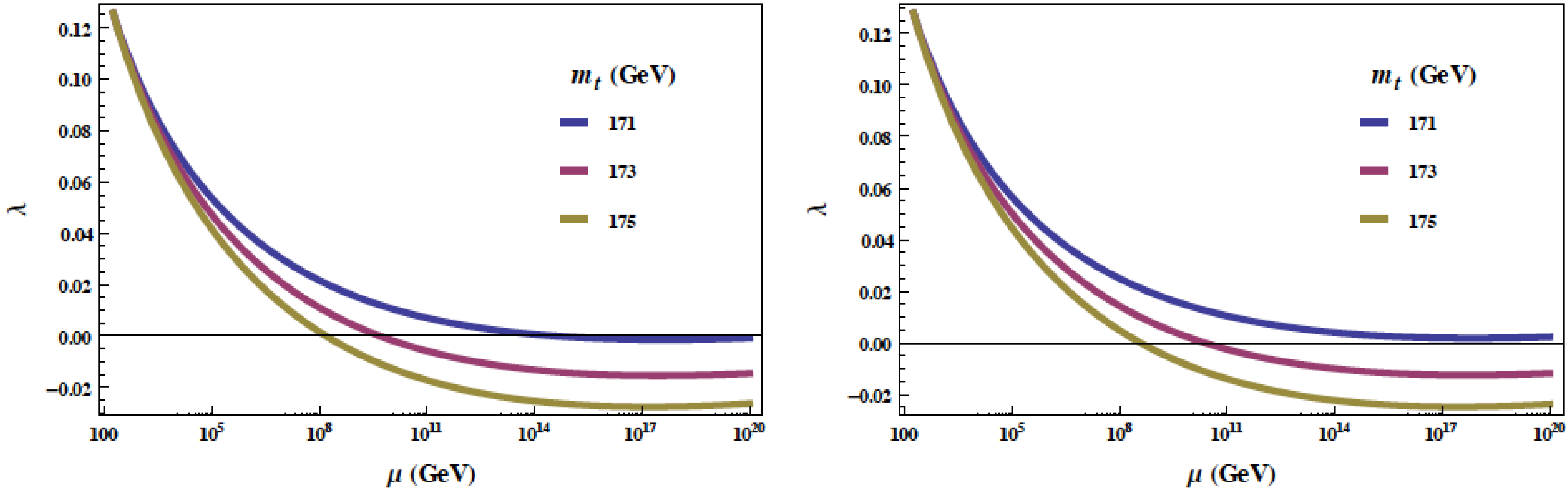
$$V_{\rm H}^{(1-\text{loop})}(h) = \frac{\lambda(h)}{8}\left(h^2 - v_{EW}\right)^2 \ ,$$

$$\lambda(h) = \lambda(\mu) + \beta_\lambda \ln(h/\mu)$$

$$(4\pi)^2\beta_\lambda = -6y_t^4 + 24\lambda^2 + \ldots$$

$$y_t(m_t) \approx 1 \ , \ \ \lambda(m_h) \approx 0.13 \ \longrightarrow \beta_\lambda < 0$$

Vacuum stability



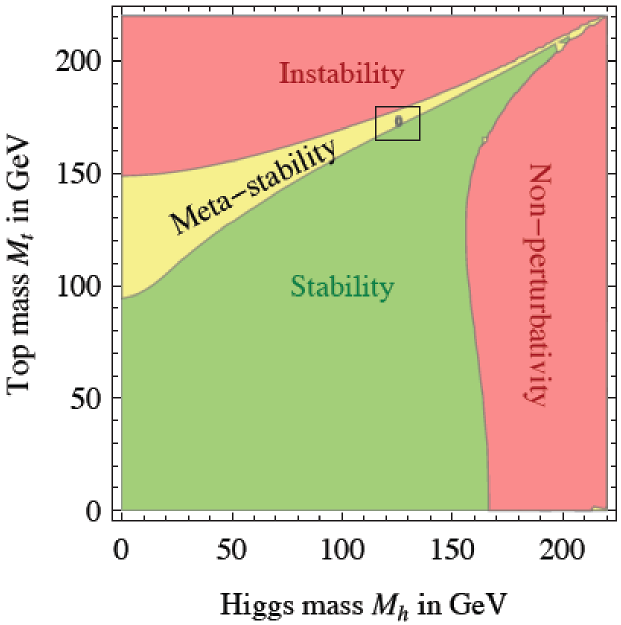
(a) $m_h = 125$ GeV (b) $m_h = 126$ GeV

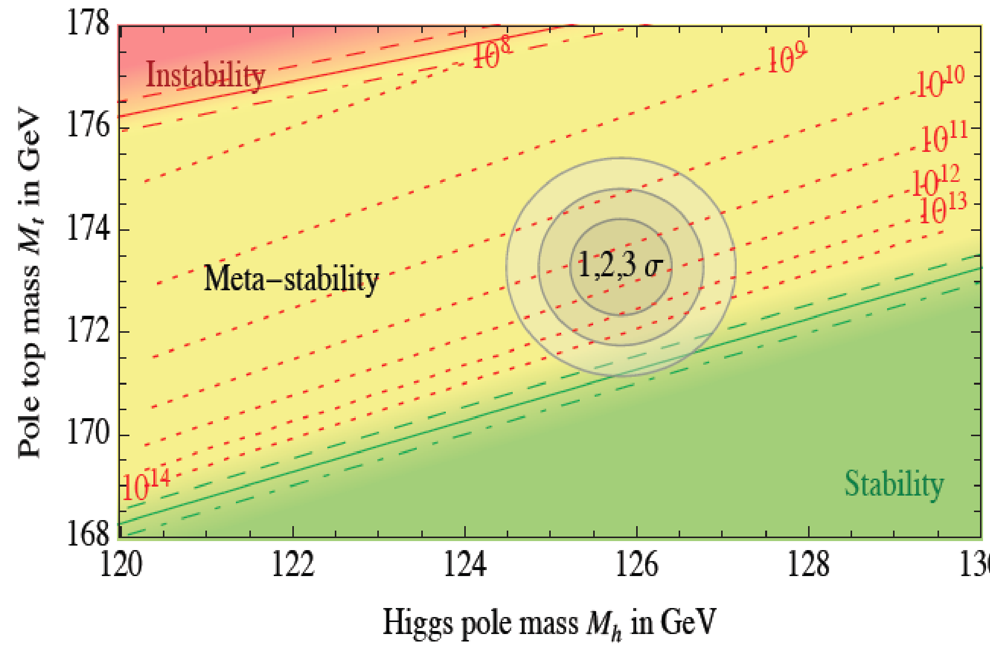
Figure 1: Two loop running of the Higgs quartic coupling in the SM.

AK & A. Spencer-Smith, arXiv:1305.7283

Instability scale $\lambda(\mu_i) = 0, \;\; \mu_i \approx 10^{10}$ GeV

Vacuum stability





$$M_h \ [\text{GeV}] > 129.8 + 1.4 \left(\frac{M_t \ [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$

$$M_h = 125.8 \pm 0.4 \, \text{GeV} \qquad \text{(naive average of latest results)}$$

For m_h < 126 GeV, stability up to the Planck mass is excluded at 98% C.L. – J. Elias-Miro, et al, JHEP 1206 (2012) 031 [arXiv:126497]

Vacuum stability

- The main uncertainty is in M_t

$$M_t = \begin{cases} 173.2 \pm 0.9 \text{ GeV} & \text{Tevatron} \\ 173.2 \pm 0.94 \text{ GeV} & \text{CMS} \\ 174.5 \pm 2.4 \text{ GeV} & \text{ATLAS} \end{cases}$$

- Hard to measure accurately at LHC – Monte Carlo reconstruction of M_t from top decay products that contain jets, neutrinos and initial state radiation
- Top-quark is not a free particle, hence strictly no pole mass exists! This introduces uncertainties $\pm\Lambda_{\rm QCD} \approx 0.3 \text{ GeV}$
- More promising is to improve accuracy of theoretical calculations, e.g., running in 2-loop mass-dependent renormalization scheme (A. Spencer-Smith, work in progress)

Vacuum stability

- Large field limit:

$$V_{\mathrm{H}} = \frac{\bar{\beta}_\lambda \ln(h/\mu_i)}{4} h^4 \ , \ \bar{\beta}_\lambda = \beta_\lambda|_{\mu=\mu_i}$$

$$h_* = \mu_i e^{-1/4}$$

- Using Coleman's prescription, one can calculate that the decay of electroweak vacuum is dominated by small size Lee-Wick bounce solution,

$$R \sim 1/\mu_m \approx 10^{-17}/\mathrm{GeV}, \ \beta_\lambda|_{\mu=\mu_m} = 0$$

$$S_{\mathrm{LW}} = \frac{8\pi^2}{3|\lambda(\mu_m)|}, \ |\lambda(\mu_m)| \approx 0.01 - 0.02$$

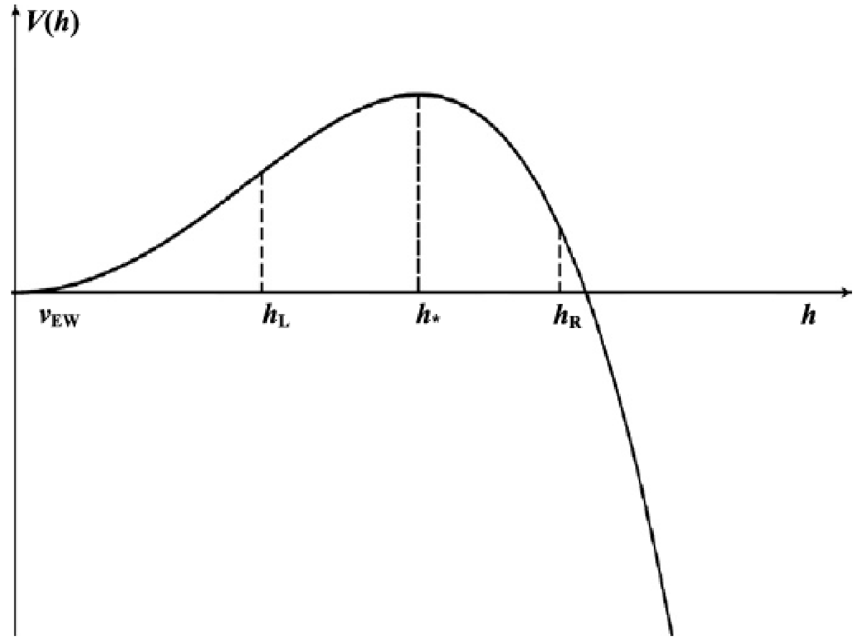


Fig. 1. The Higgs potential. For large values of the Higgs field h, the electroweak vacuum configuration is regarded as trivial, $v_{\mathrm{EW}} \approx 0$.

$$P_{\mathrm{EW}} = e^{-p} \approx 1, \ p = (\mu_m/H_0)^4 \exp(-S_{\mathrm{LW}}) << 1$$

Electroweak vacuum in the Standard Model is metastable!

Vacuum stability

- Electroweak vacuum decay may qualitatively differ in cosmological spacetimes:

  (i) Thermal activation of a decay process, $T_r < \mu_i$

  (ii) Production of large amplitude Higgs perturbations during inflation,

  $H_{\inf} < \mu_i$ [J.R. Espinosa, G.F. Giudice, A. Riotto, JCAP 0805 (2008) 002]

  The bound that follows from the above consideration can be avoided, e.g., in curvaton models, or when $m_h^{\rm eff} > H_{\inf}$

- Actually, the dominant decay processes are due to instantons, (Hawking-Moss, or more generic CdL) [AK & A. Spencer-Smith, Phys Lett B 722 (2013) 130 [arXiv:1301.2846]]

$$V(h,\phi) = V_{\rm H}(h) + V_{\inf}(\phi) + V_{\rm H-inf}$$

$$V_{\inf}(\phi) = \mathcal{V}_{\inf} + V'_*(\phi - \phi_{\inf}) + 1/2V''_*(\phi - \phi_{\inf})^2 + ...$$

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'_*}{\mathcal{V}_{\inf}}\right)^2 << 1, \quad -1 << \eta = M_P^2\frac{V''_*}{\mathcal{V}_{\inf}} << 1$$

Vacuum stability

- Fixed background approximation: $\phi = \phi_{\rm inf}, \; ds^2 = d\chi^2 + \rho^2(\chi) d\Omega_3,$

$$\rho(\chi) = H_{\rm inf}^{-1} \sin(H_{\rm inf}\chi), \; \chi = t^2 + r^2, \; \chi \in [0, \pi/H_{\rm inf}], \; H_{\rm inf}^2 = \mathcal{V}_{\rm inf}/3M_P^2$$

- EoM for Higgs field:

$$\ddot{h} + 3H_{\rm inf} \cot(H_{\rm inf}\chi)\dot{h} = \frac{\partial V(\phi_{\rm inf}, h)}{\partial h}$$

$$\dot{h}(0) = \dot{h}(\pi/H_{\rm inf}) = 0$$

$$h_L(x_*) = h_R(x_*)$$

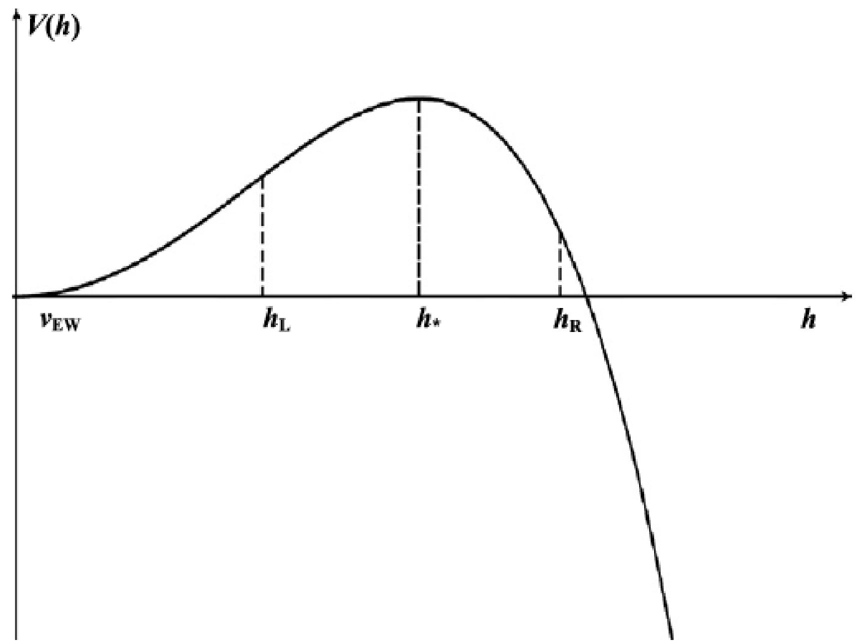


Fig. 1. The Higgs potential. For large values of the Higgs field h, the electroweak vacuum configuration is regarded as trivial, $v_{EW} \approx 0$.

Vacuum stability

- Hawking-Moss instanton: $\frac{\partial V}{\partial h} = 0\ , h(x) = h_*,$

$$p \approx \exp\left\{-\frac{8\pi^2}{3}\frac{V_{\rm H}(h_*) + V_{\rm H-inf}(\phi_{\rm inf}, h_*)}{H^4_{\rm inf}}\right\}$$

- For $V_{\rm H-inf}(\phi_{\rm inf}, h_*) << V(h_*)$,

HM transition generates a fast decay of the electroweak vacuum, unless

$$H_{\rm inf} < 10^9(10^{12})\ \rm GeV$$

$$m_h = 126\ \rm GeV, \quad m_t = 174(172)\ \rm GeV$$

- Together with $n_s < 1$, this implies that only small-field inflationary models are allowed with a negligible tensor/scalar: ,

$$r < 10^{-11}(10^{-5})$$

Vacuum stability

- Consider, $V_{\mathrm{H-inf}} = \frac{\alpha}{2} h^2 \phi^2 \ (\alpha > 0), \ m_h^{\mathrm{eff}} = \alpha^{1/2}\phi_{\mathrm{inf}} > H_{\mathrm{inf}}$

[O. Lebedev & A. Westphal Phys.Lett. B719 (2013) 415]

$$h_* = (-\alpha/\lambda)^{1/2}\phi_{\mathrm{inf}} > \mu_i, \ (\lambda(h_*) < 0)$$

- Large-field chaotic inflation $\left[V_{\mathrm{inf}} = 1/2 m_\phi^2 \phi^2, \ m_\phi = 10^{-5} M_{\mathrm{P}}\right]$, with

$$\alpha > 1.4\sqrt{|\lambda|}\,(H_{\mathrm{inf}}/\phi_{\mathrm{inf}})^2 > 6 \cdot 10^{-12} \ .$$

- Naturalness constraint:

$$\alpha < 64\pi^2\,(m_\phi/m_h)^2 \approx 2 \cdot 10^{-20}$$

Tuning is needed!

Vacuum stability

- In the limit $m_h^{\text{eff}} >> H_{\text{inf}}$

$$h'' + 3h'\chi = \frac{\partial V(\phi_{\text{inf}}, h)}{\partial h}, \quad [x = m_h^{\text{eff}}\chi]$$

$$h(x) = \begin{cases} 8h_{\mathrm{R}}\left(8 + \left(\frac{h_{\mathrm{R}}}{h_*}\right)^2 x^2\right)^{-1}, & 0 \leq x < x_* \\ \frac{x_* h_*}{x(J_1(ix_*)+iY_1(-ix_*))}\left(J_1(ix) + iY_1(-ix)\right), & x_* < x < \infty \end{cases},$$

$$x_* = \frac{2\sqrt{2}h_*}{h_{\mathrm{R}}}\left(\frac{h_{\mathrm{R}}}{h_*} - 1\right)^{1/2}.$$

$$B_{\mathrm{CdL}} = -\frac{2\pi^2}{\lambda}I < 0, \quad I = \int_0^\infty x^3 dx \left[h^2(x)\left(1 - \frac{h^2(x)}{2h_*^2}\right)\right] < 0, \quad \lambda(\mu > \mu_i) < 0.$$

$$p \propto \exp\{-B_{\mathrm{CdL}}\} >> 1$$ EW vacuum is unstable!

Vacuum stability

- Fast decay of EW ceases inflation globally (no eternal inflation)

$$\mathrm{e}^{3H_{\mathrm{inf}}\tau}\mathrm{e}^{-(\tau H_{\mathrm{inf}})^4 p}$$

$$\tau_{\mathrm{stop}} \approx (3/p)^{1/3} H_{\mathrm{inf}}^{-1} < 1.4 H_{\mathrm{inf}}^{-1}$$

- The above considerations applies to models with curvaton

Vacuum stability

- For the 'unperturbed' SM potential the condition of vacuum metastability rules out all large scale models.
- All models with sizeable Higgs-inflaton interactions are ruled out.
- An observation of tensor perturbations in the CMB by the Planck satellite would provide a strong indication of new physics beyond the Standard Model.

Vacuum stability and neutrino masses

(A.K., A. Spencer-Smith, JHEP, 2013 in press [arXiv:1305.7283])

- Oscillation experiments show that neutrinos are massive. Massive neutrinos cannot be accommodated within the Standard Model

- Type I see-saw mechanism – new heavy right-handed neutrinos – worsens vacuum stability

- Type III see-saw mechanism – new electroweak triplet fermions – light triplet fermions are required

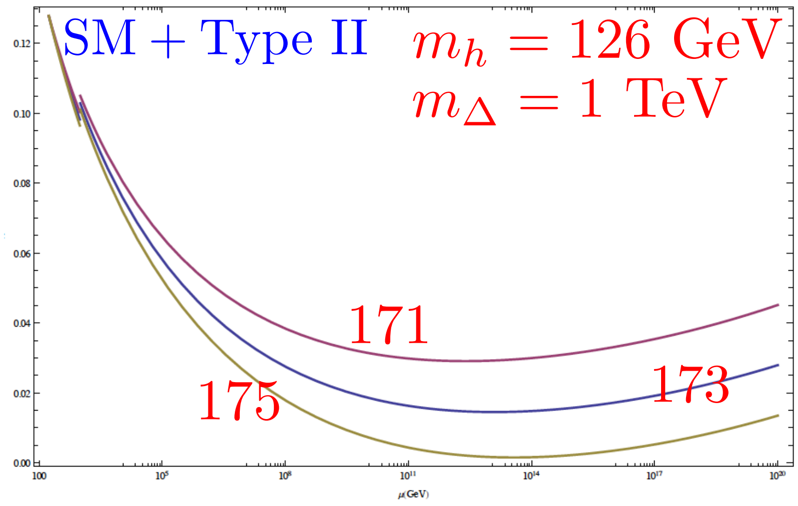
- Type II see-saw – new electroweak triplet boson – capable to solve the stability problem:

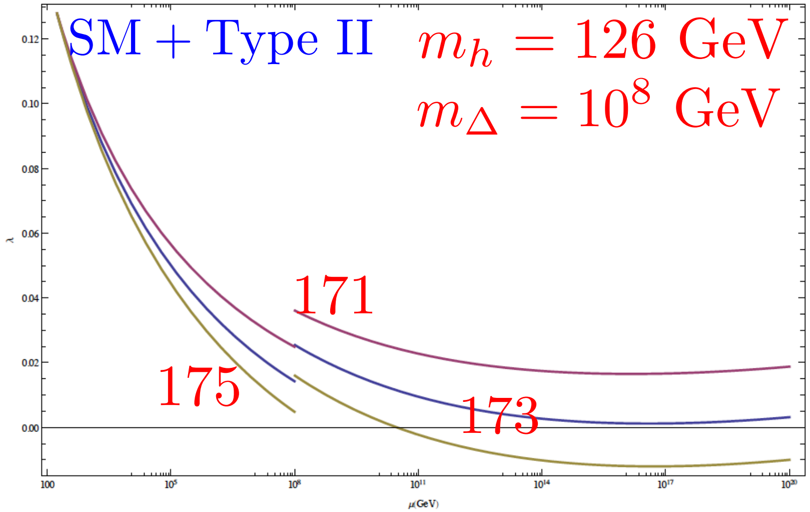
  (i) threshold (classical) correction to Higgs self-interaction coupling;

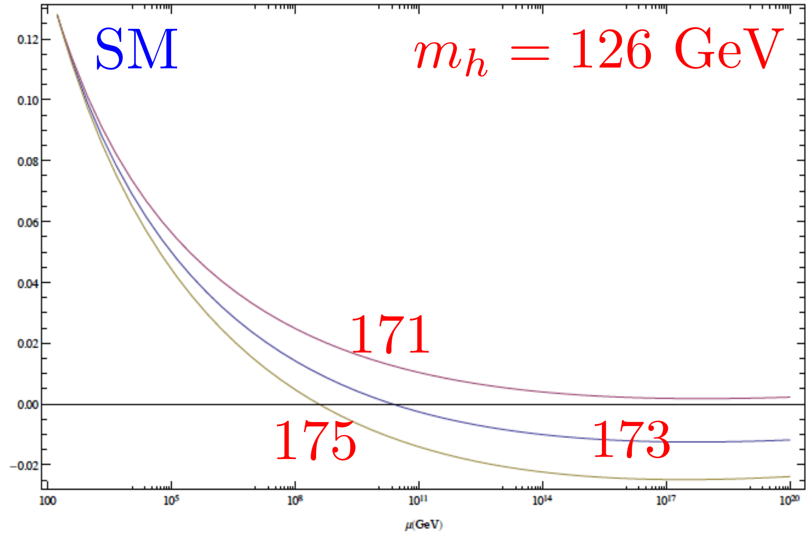
  (ii) positive contribution to β_λ

Vacuum stability and neutrino masses

(A.K., A. Spencer-Smith, JHEP, 2013 in press [arXiv:1305.7283])







Higgs inflation?

Suppose M_t < 171 GeV, then EW vacuum is stable and Higgs can drive inflation

A) Higgs slowly rolls down (tunnels) from the plato (local minimum), where

$$\lambda(M_P) = \beta_\lambda(M_P) \approx 0$$

and produces inflation (Masina, Notari). In tension with data.

B) Higgs has large non-minimal coupling to gravity, $\xi(H^\dagger H)R$, which effectively flattens the Higgs potential (Bezrukov, Shaposhnikov) [Needs an extra scalar to avoid strong coupling regime]

C) New particles can postpone the instability scale. Higgs can roll from the local maximum down to the electroweak minimum (Blanco-Pillado, A.K.)

Higgs inflation is highly predictive scenario which can be falsified in precision cosmological measurements

Naturalness

- Higgs with m_h=125-126 GeV is somewhat heavy than in typical supersymmetric models (see, P. Athron's & A. Medina's talks, however) and somewhat light than typical prediction of technicolour models (see, T. Sankar's talk, however).

- People started to question the validity of the naturalness principle

- My personal point of view: The naturalness principle has adopted as a guiding principle for new physics not because to produce more papers or/and to fool experimentalists. It reflects our current understanding of basics of QFT. A failure of naturalness would mean that these basics must be fundamentally reviewed.

Naturalness

- P. Dirac was the first who recognised importance of naturalness in quantum physics. He asserted that all the dimensionless parameters of a theory must be of the same order of magnitude (strong naturalness principle) – why? – because in quantum theory all the parameters are related to each other via quantum corrections!

- Dirac's Large (Small) Number Hypothesis:

EM / Gravity: $\alpha\left(\frac{m_e}{M_P}\right)\left(\frac{m_p}{M_P}\right)\approx 10^{-40}$ is = $\left(\frac{m_p}{M_U}\right)^{1/2}\approx 10^{-40}$

Predicts time-variation of microscopic constants, which turned out to be wrong!

- Lesson: The principle applies to microscopic parameters. Macroscopic parameters, such as mass of the universe M_U can be random (maybe CC is the same?).

Naturalness

- G. t'Hooft: Dimensionless parameter can be small if it is supported by a symmetry (technical naturalness).

$$\left(\frac{m_e}{M_P}\right) << 1$$ -- chiral symmetry

$$\left(\frac{m_p}{M_P}\right) << 1$$ -- dimensional transmutation in QCD, aka scale invariance

- Naturalness of EWSB:

$$\left(\frac{m_h}{M_P}\right) << 1$$ -- ???

Naturalness

- Consider an effective theory with a 'physical' cut-off Λ, which contains scalars, S, fermions, F, and vector fields, V.

- 1-loop scalar mass terms:

$$m_S^2(\mu) = m_S^2(\Lambda) + \frac{1}{32\pi^2}\mathrm{STr}\; g_A \;\left[\Lambda^2 - M_A^2 \log(\Lambda^2/\mu^2)\right]$$

$$\mathrm{STr} \equiv (-1)^{2J_A}(2J_A+1)$$

- $m_S^2 << \Lambda^2$ is unnatural (hierarchy problem)

- According to t'Hooft, we need a symmetry to remove quadratic dependence on UV scale

Naturalness

- Supersymmetry:

Non-renormalization theorem: $\mathrm{STr}\ g_A = 0$ (holds in softly-broken SUSY!)

$$\mathrm{STr}\ g_A M_A^2 = 0$$

Quadratic divergences are absent in softly-broken SUSY

- Scale invariance:

$$m_S^2(\mu = \Lambda) = 0 \longrightarrow \bar{m}_S^2(\Lambda) + \mathrm{Str}\ g_A\ \Lambda^2 = 0$$

Scale invariance is broken spontaneously and explicitly by logarithmic quantum corrections, $T_\mu^\mu = \sum_i \beta_i \mathcal{O}_i$, – dimensional transmutation

Interesting model building/pheno [R. Foot, A.K., K.L. McDonalds, R.R. Volkas]

Conclusion

- The LHC resonance at 125-126 GeV looks as SM-like Higgs boson. There is still room for 30 to 50% (large!) deviations

  - Measurement of couplings

  - Spin/parity (non-minimal spin 2, mixed parity)

  - Constraints from unitarity (VV-scattering) on heavy resonances

- Interesting interplay between Higgs physics and cosmology: The electroweak vacuum stability may also be hinting towards physics beyond the Standard Model (e.g., associated with neutrino mass generation, strong CP problem, dark matter, etc…). PLANCK satellite may provide a crucial information soon.

  - More precise calculations of SM running parameters

  - New physics model building

  - Higgs inflation

- Naturalness is important

  - New physics model building (scale invariance, composite models alternative SUSY)

  - Collider phenomenology

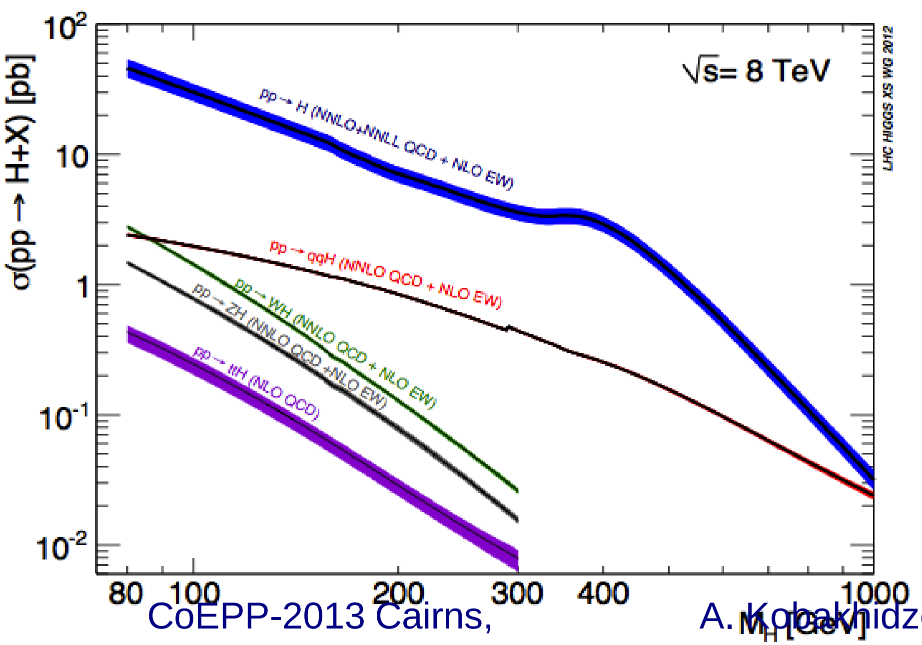
BACKUP SLIDES

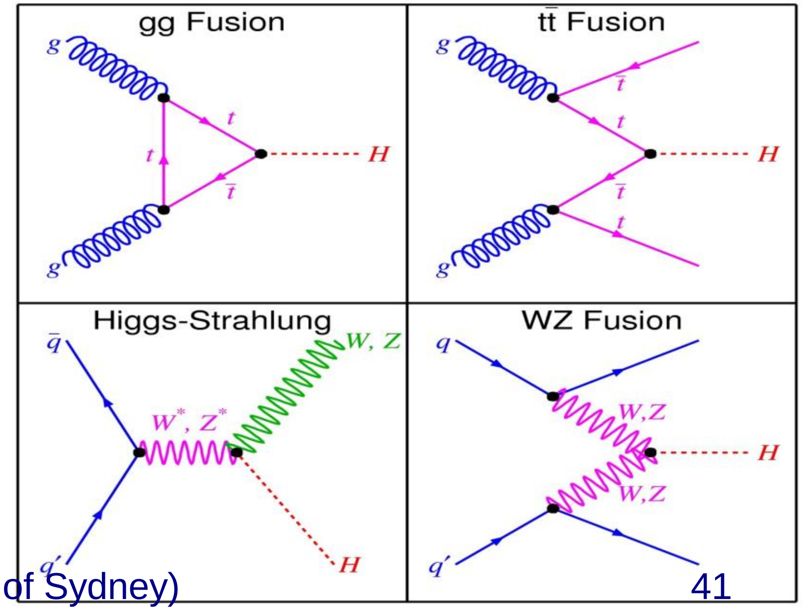
Couplings to SM fields

- Couplings are SM-like, but still there is a room for 30 to 50% deviations!
- Suppose, $\mu_{WW} = \mu_{ZZ} = 1$ and $\mu_{\gamma\gamma} \cong 1.5$. What does this imply?

$$\mu_{XX} = \frac{\sigma(pp\to h)}{\sigma_{SM}(pp\to h)}\,\frac{\Gamma(h\to XX)}{\Gamma_{SM}(h\to XX)}\,\frac{\Gamma_{SM}(h\to all)}{\Gamma(h\to all)}$$

$$\sigma(pp\to h)\approx\sigma(gg\to h)\overset{\Gamma\ll m_h}{\approx}\frac{\pi^2}{8m_h}\Gamma(h\to gg)\,\delta(s-m_h^2)$$





Couplings to SM fields

- Can we explain the data within the SM without new particles, just modifying tree-level couplings, y_t and g_{hVV} ?

$$\frac{\mu_{\gamma\gamma}}{\mu_{VV}} = \left(1.28 - 0.28\frac{r_t}{r_V}\right)^2 \approx 1.5 - 2.$$

$$\frac{r_t}{r_V} \sim 0.2 \quad \wedge \quad \frac{r_t}{r_V} \sim 9$$

- Theory: linearly realised SU(2)XU(1) gauge symmetry implies that coupling constants are proportional to masses, e.g. $y_t \sim M_t$ and $g_{hVV} \sim M_V$ and $|r_t|$, $|r_V| <= 1$.

Couplings to SM fields

- Conclusion: $\mu_{\gamma\gamma}$ can be enhanced only by introducing new charged particles, $X^{\gamma\gamma}_{other}$

- S. Dawson and E. Furlan, Phys. Rev. D 86, 015021 (2012) [arXiv:1205.4733 [hep-ph]];
- M. Carena, I. Low and C. E. M. Wagner, JHEP 1208, 060 (2012) [arXiv:1206.1082 [hep-ph]];
- H. An, T. Liu and L. -T. Wang, arXiv:1207.2473 [hep-ph];
- A. Joglekar, P. Schwaller and C. E. M.Wagner, arXiv:1207.4235 [hep-ph];
- N. Arkani-Hamed, K. Blum, R. T. D'Agnolo and J. Fan, arXiv:1207.4482 [hep-ph];
- L. G. Almeida, E. Bertuzzo, P. A. N. Machado and R. Z. Funchal, arXiv:1207.5254 [hep-ph];
- J. Kearney, A. Pierce and N. Weiner, arXiv:1207.7062 [hep-ph];
- I. Dorsner, S. Fajfer, A. Greljo and J. F. Kamenik, arXiv:1208.1266 [hep-ph];
- M. Reece, arXiv:1208.1765 [hep-ph];
- A. Barroso, P. M. Ferreira, R. Santos and J. P. Silva, Phys. Rev. D 86, 015022 (2012);
- D. McKeen, M. Pospelov and A. Ritz, arXiv:1208.4597 [hep-ph];
- M. B. Voloshin, arXiv:1208.4303 [hep-ph]; …

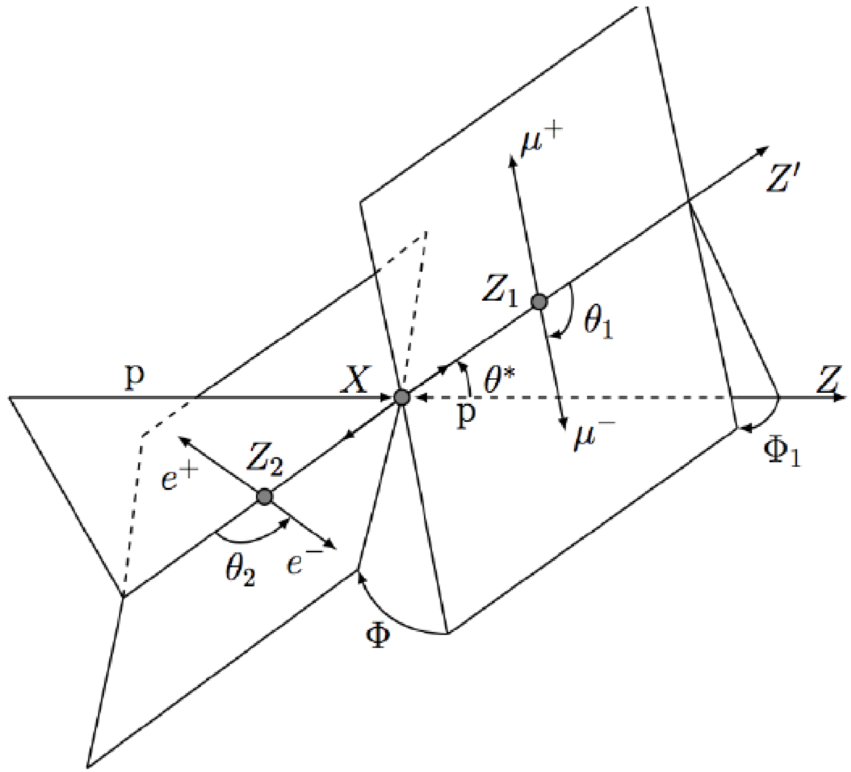


Figure 13: Definition of the production and decay angles in an $X \to ZZ^{(*)} \to 4\ell$ decay. The illustration is drawn with the beam axis in the lab frame, the Z_1 and Z_2 in the X rest frame and the leptons in their corresponding parent rest frames (see text for further description).

Naturalness and the scale invariance

- Wilsonian effective theory with cut-off scale Λ:

$$Z_\Lambda[J_S] = \int DS \ \exp\left(i \int d^4x \ [\mathcal{L}_\Lambda + J_S S]\right)$$

$$\mathcal{L}_\Lambda = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m^2(\Lambda)S^2 - \frac{\lambda(\Lambda)}{4}S^4 + \ldots$$

- Compute quantum corrections:

$$m_R^2(\mu) = m^2(\Lambda) + \frac{3\lambda}{16\pi^2}\left[\Lambda^2 - m^2(\Lambda)\log\left(\Lambda^2/\mu^2\right)\right]$$

- Thus, a light scalar,

$$m_R^2 << \Lambda^2$$

is "unnatural" (hierarchy problem)

Naturalness and the scale invariance

- Suppose the underline theory is scale-invariant:

$$Z[J_S, J_H] = \int [DS\ DH] \exp\left(i \int d^4x\ [\mathcal{L} + J_S S + J_H H]\right)$$

$$\mathcal{L}[tS, tH] = t^4 \mathcal{L}[S, H]$$

- Then

$$m_R^2(\Lambda) = 0 = m^2(\Lambda) + \frac{3\lambda}{16\pi^2}\Lambda^2$$

is a natural renormalization condition which is imposed due to the absence of a mass parameter in the scale-invariant bare Lagrangian [Foot, A.K., Volkas; Meissner, Nicolai, 2007].

- (Anomalous) Ward-Takahashi identity [W.A. Bardeen, 1995]:

$$T^\mu_\mu = \sum_i \beta_i(\lambda)\mathcal{O}_i$$

- Masses are generated from spontaneous breaking of scale invariance through the mechanism of dimensional transmutation.

Scale-invariant models

- Minimal scale-invariant Standard Model [R. Foot, A. K., R.R. Volkas, Phys. Lett. B655 (2007)156-161]:

$$V_0 = \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{4}S^4 + \frac{\lambda_3}{2}\left(\phi^\dagger\phi\right)S^2 = \frac{r^4}{8}\left(\lambda_1\cos^4\theta + 2\lambda_2\sin^4\theta + 2\lambda_3\sin\theta\cos\theta\right)$$

- Demanding cancellation of the cosmological constant the dilaton mass is generated at 2-loop. A light dilaton is a generic prediction of such class of models [R. Foot, A. K., arXiv:1112.0607].

$$V_{\text{min}} = -2B = 0 \Longrightarrow \quad m_r^2 = 8C\langle r\rangle^2$$

$$m_r \approx 7 - 10 \text{ GeV}$$

- Higgs mass prediction: $m_h \approx 12^{1/4} m_t \approx 300 \text{ GeV}$

Excluded by LHC

Dark matter: Scale-invariant mirror world

- Scale-invariant scalar potentials are automatically invariant under discrete Z_2 symmetry. If Z_2 is unbroken some heavy scalar states are stable and can play the role of dark matte.

- However, some recent experiments (DAMA/LIBRA, CoGeNT) provide evidence for light (7-15 GeV) dark matter particles. The best explanation of these experiments is provided by the mirror dark matter models [R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B272, (191) 67; R. Foot, Phys. Rev. D 78 (2008) 043529; Phys. Lett. B692 (2010)].

- Scale-invariant mirror world models are discussed in: R. Foot, A.K. and R. R. Volkas Phys. Lett. B655 (2007)156-161; Phys. Rev. D82 (2010) 035005 and R. Foot, A. K., arXiv:1112.0607. Extended scalar sector has further motivation due to the mirror symmetry doubling.
- Higgs sector, besides the light dilaton, contains two neutral Higgs scalars:

$$m_H = (24 m_t^4 - m_h^4)^{1/4} \approx 355 \text{ GeV}$$

Neutrino masses in scale-invariant models

- Different possibilities of neutrino mass generation is discussed in R. Foot, A. K., K.L. McDonald, R.R. Volkas, Phys. Rev. D76 (2007) 075014.

- One particular model contains extra electroweak triplet scalar particle Δ(type II see-saw) [R. Foot, A. K., arXiv:1112.0607]:

$$m_\Delta = (2m_t^4 - m_h^4/6)^{1/4} \approx 190 \text{ GeV}$$