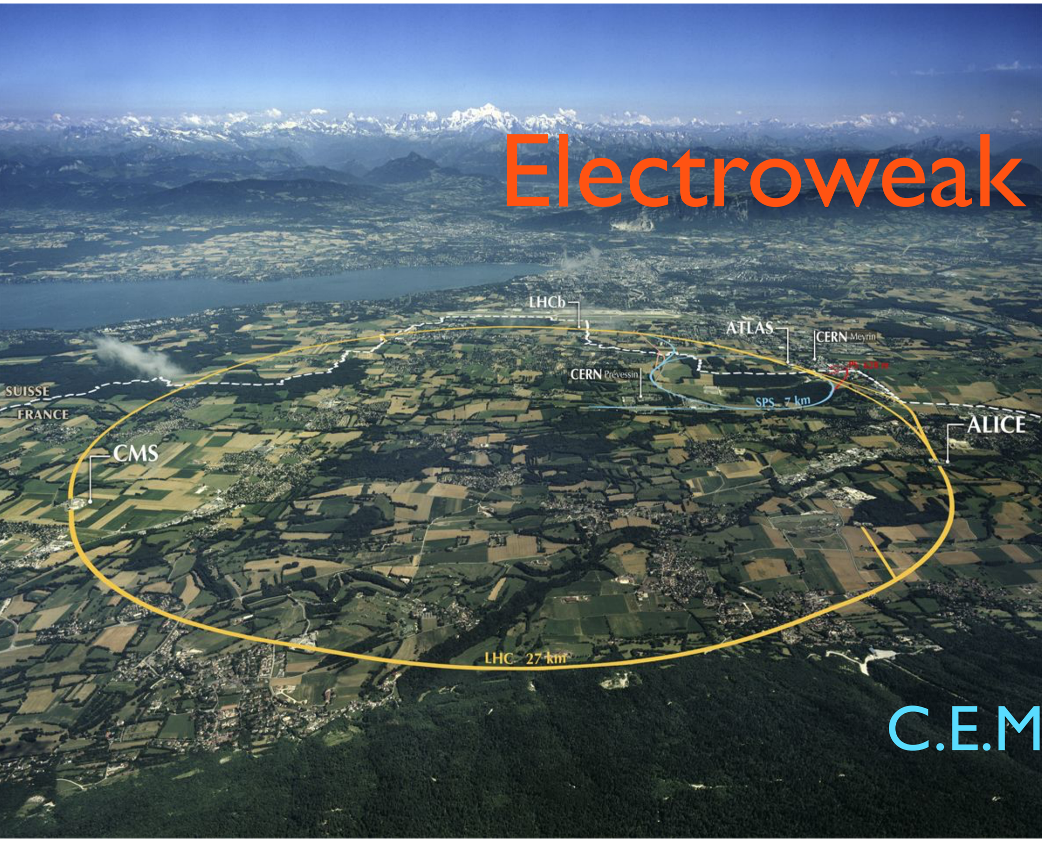
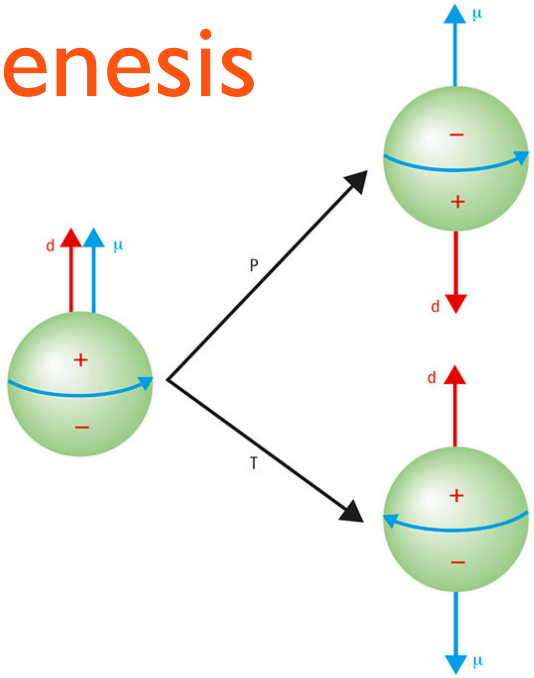
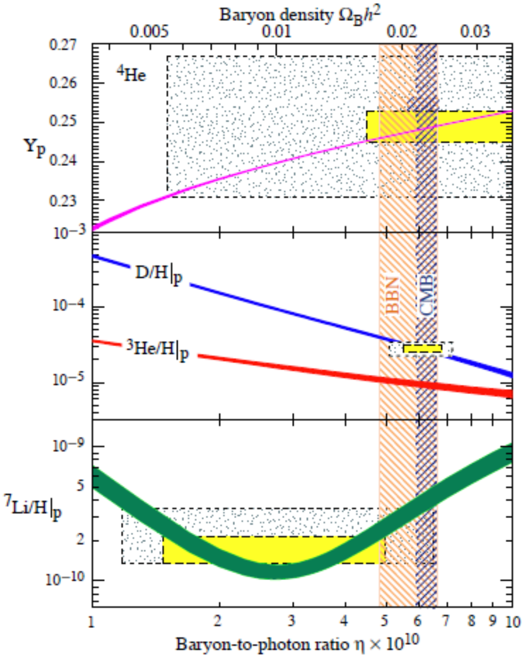
Electroweak Baryogenesis

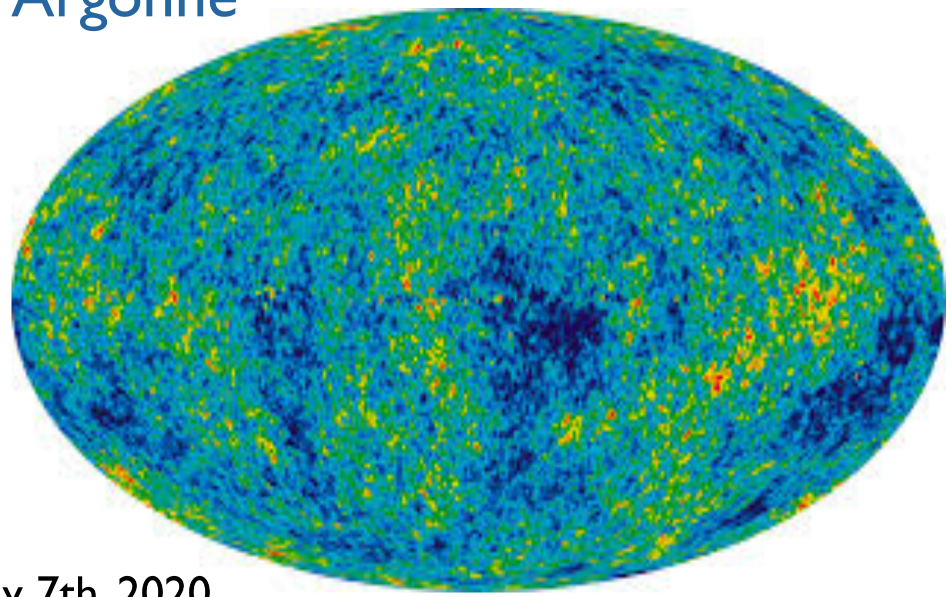




C.E.M. Wagner

EFI & KICP , Univ. of Chicago
HEP Division, Argonne





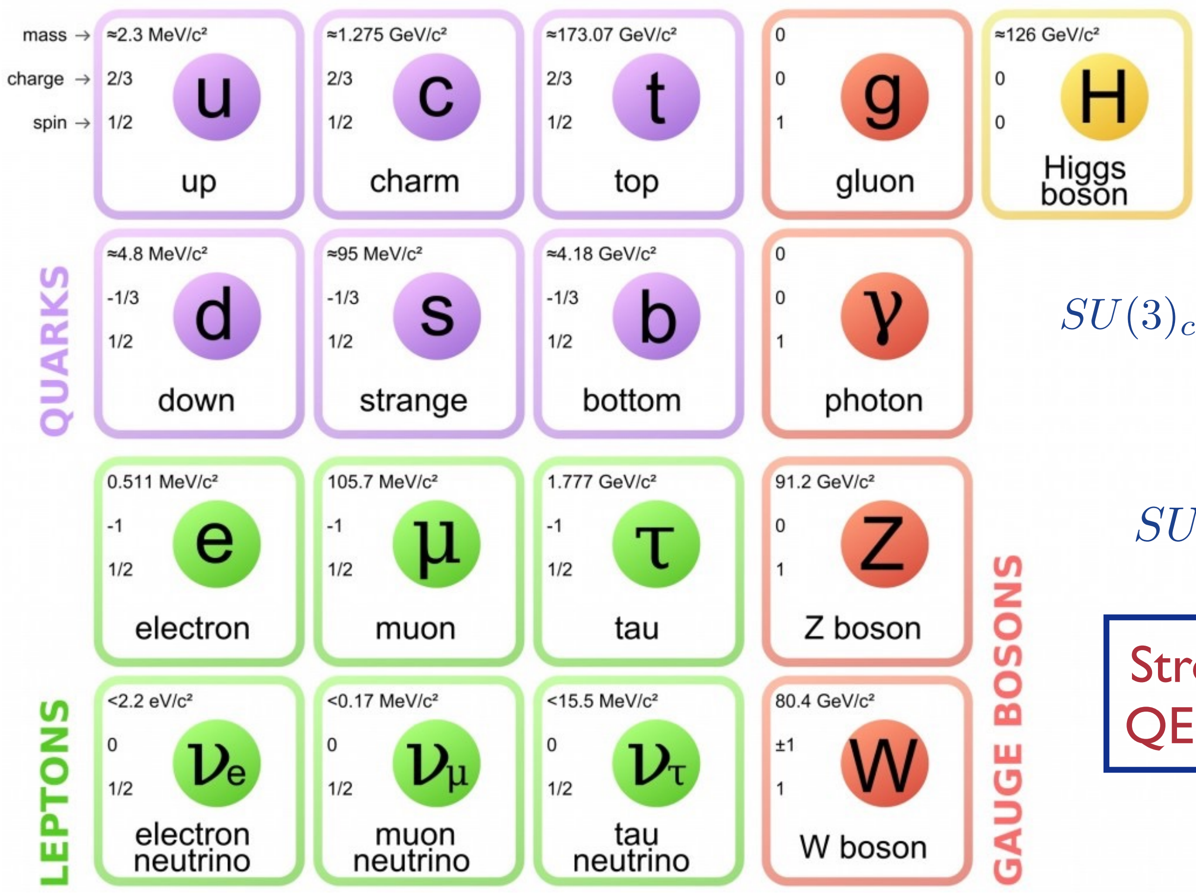
BLV workshop, July 7th, 2020

The Standard Model

Is an extremely successful Theory that describes interactions between the known elementary particles.

3 generations of fermions (mattter)

Gauge and Higgs Fields



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS

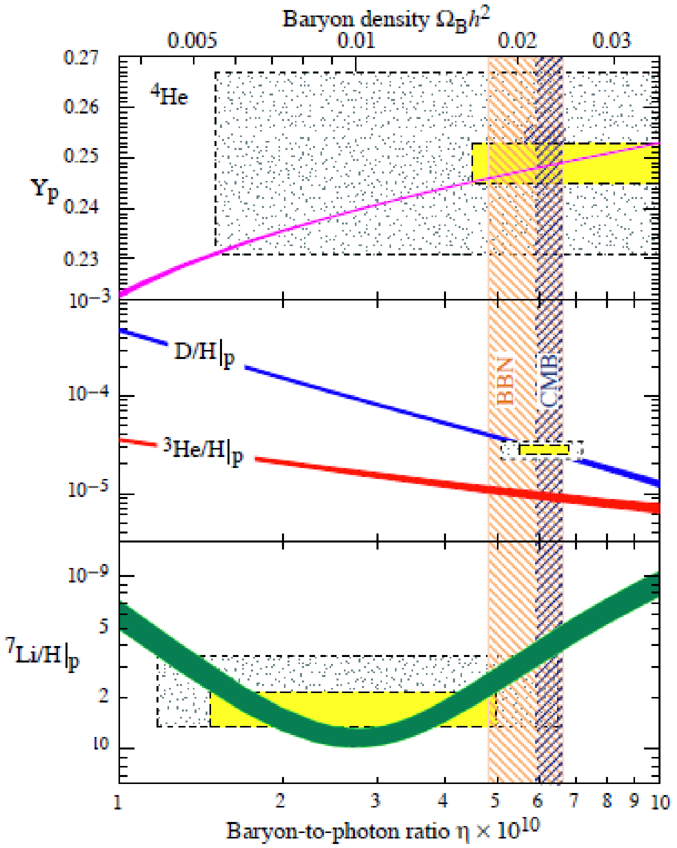
$$\begin{tikzcd} SU(3)_c \times SU(2)_L \times U(1)_Y \arrow[d, "< H >= \frac{v}{\sqrt{2}}"] \\ SU(3)_c \times U(1)_{\text{em}} \end{tikzcd}$$

Strong, Weak and QED Interactions

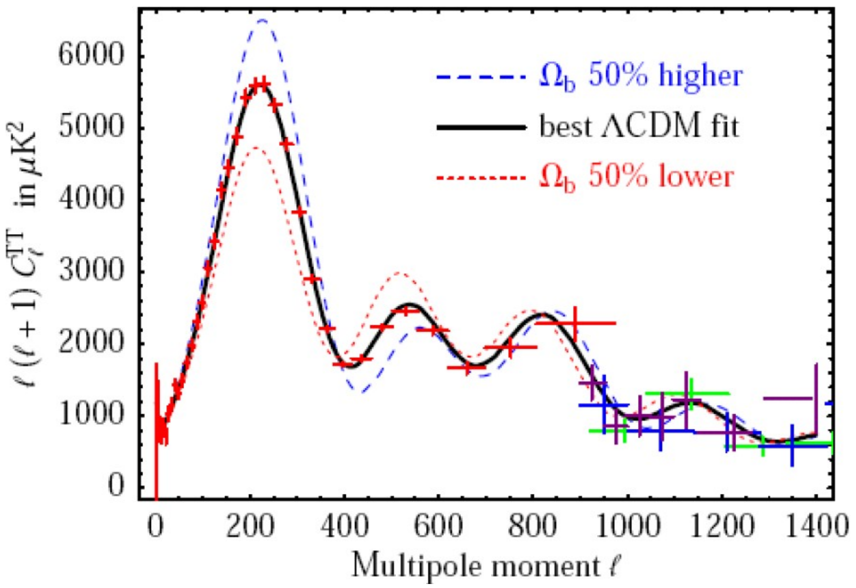
Open Question :
Origin of Ordinary Matter

Where is the Antimatter ?

Nucleosynthesis
Abundance of light elements



Peaks in CMB power spectrum



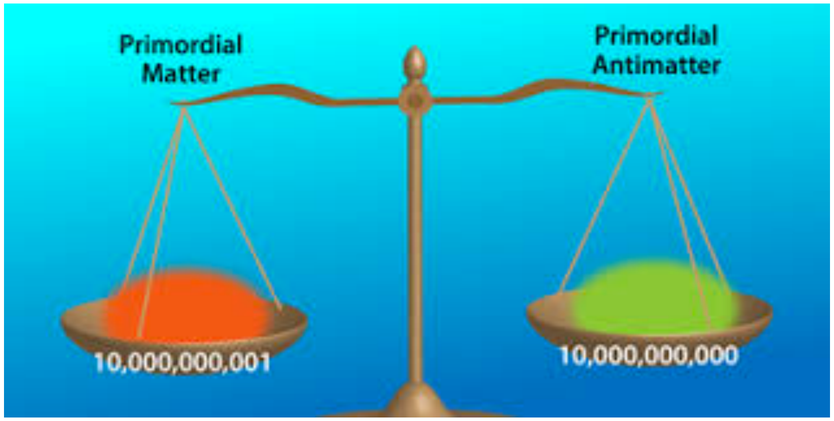
$$\boxed{\eta_B = (6.11 \pm 0.19) \times 10^{-10}}$$

$$\eta_B = \frac{n_B}{n_\gamma}$$

- How to explain the appearance of such a small quantity ?

Generating the Matter-Antimatter Asymmetry

Antimatter may have disappeared through annihilation processes in the early Universe



Sakharov's Conditions

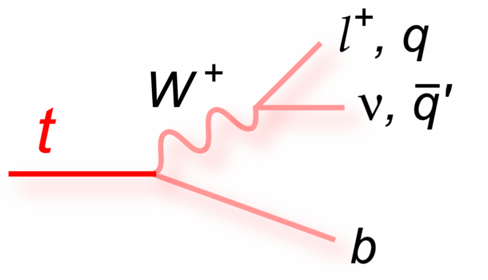
- Baryon Number Violation (Quarks carry baryon number 1/3)
- C and CP Violation
- Non-Equilibrium Processes

These three conditions are fulfilled in the Standard Model

Adler, Bardeen, Bell, Jackiw ‘69

Baryon Number Violation : Anomalous Processes

In the Standard Model, all processes we see conserve both baryon and lepton number :



For gauge theories, one finds the violation of classically preserved symmetries due to the quantization process : Anomalies.

For the chiral weak interactions, gauge symmetry preservation demands that the non-conservation of baryon and lepton currents

$$\partial_\mu j^\mu_{B,L} \propto F^a_{\mu\nu} F^a_{\rho\delta} \epsilon^{\mu\nu\rho\delta}$$

$a :$ Weak Interaction Indeces

Polyakov et al, t’Hooft ’75, 76

$$\tilde{F}_{\mu\nu} = \frac{\epsilon_{\mu\nu\rho\sigma}}{2} F^{\rho\sigma}$$

$$\text{If} \int F_{\mu\nu} \tilde{F}^{\mu\nu} \neq 0 \implies \Delta Q_{B,L} \neq 0$$

$$\Delta B = \Delta L = n \quad \text{(per generation)}$$

Baryon Number Violation at zero and finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L.. They can proceed by the production of “sphalerons”

- At zero T baryon number violating processes highly suppressed

$$S_{\rm inst} = \frac{2\pi}{\alpha_w}, \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-2S_{\rm inst})$$

- At finite T, only Boltzman suppression

T<T_{EW}

$$\frac{\Gamma_{B+L}}{V} = k\frac{M_W^7}{(\alpha T)^3}e^{-\beta E_{ph}(T)} \sim e^{\frac{-4M_W}{\alpha k T}}$$

T>T_{EW}

$$\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1} T^4$$

Proportional to $v(T)/T$

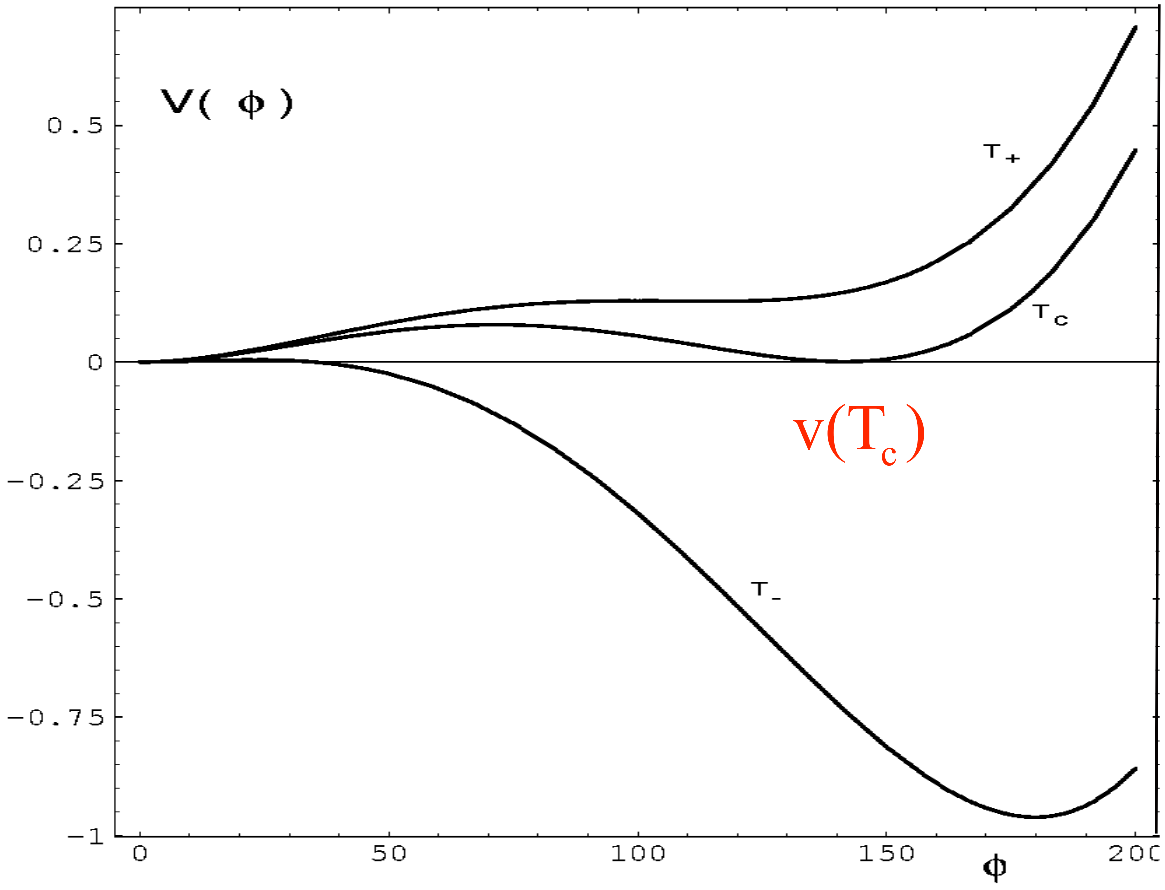
Klinkhamer and Manton ’85, Kushmin, Rubakov, Shaposhnikov’85, Arnold and Mc Lerran ’88

Baryon Number violating processes may be suppressed

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order

Phase Transition



Observe that the transition does not occur at the critical temperature, but at a somewhat lower temperature, the so called (bubble) nucleation temperature.

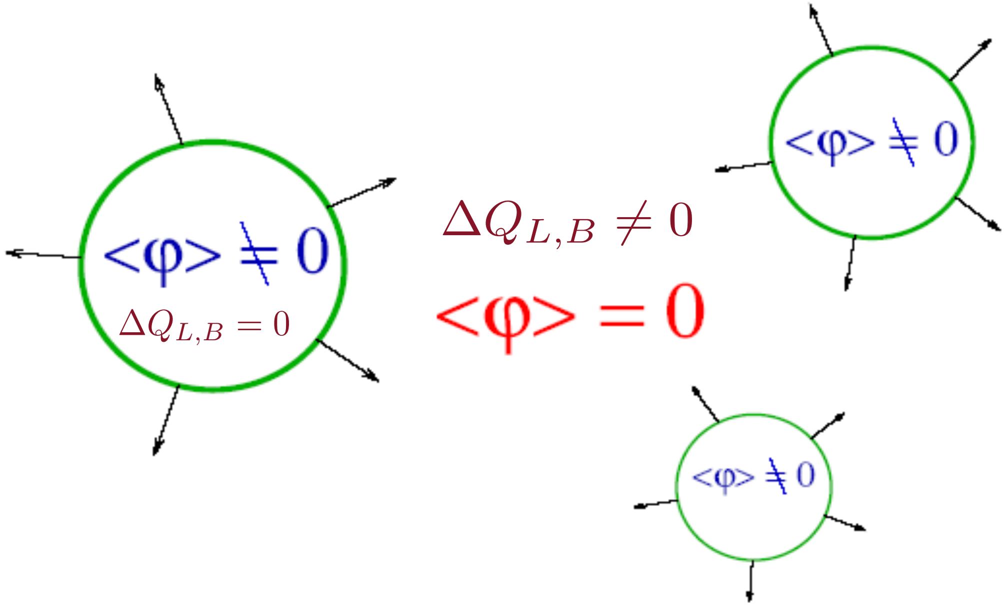
Existence of a barrier at zero temperature very relevant. Its absence ensures the transition.

Baryon Number Generation

First order phase transition :

Baryon number is generated by reactions in and around the bubble walls.

Morrissey



Kuzmin, Rubakov, Shaposhinikov'87,
Dine, Huet, Singleton '92,
Anderson, Hall'92,
Cohen, Kaplan, Nelson'93,
Huet, Nelson'95

Condition for successful baryogengesis :
Suppression of baryon number violating processes inside the bubbles

$$\frac{v(T_c)}{T_c} > 1$$

Non-Equilibrium Processes :
Strongly First Order
Electroweak Phase Transition

Finite Temperature Higgs Potential

$$V(T) \quad = \quad D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

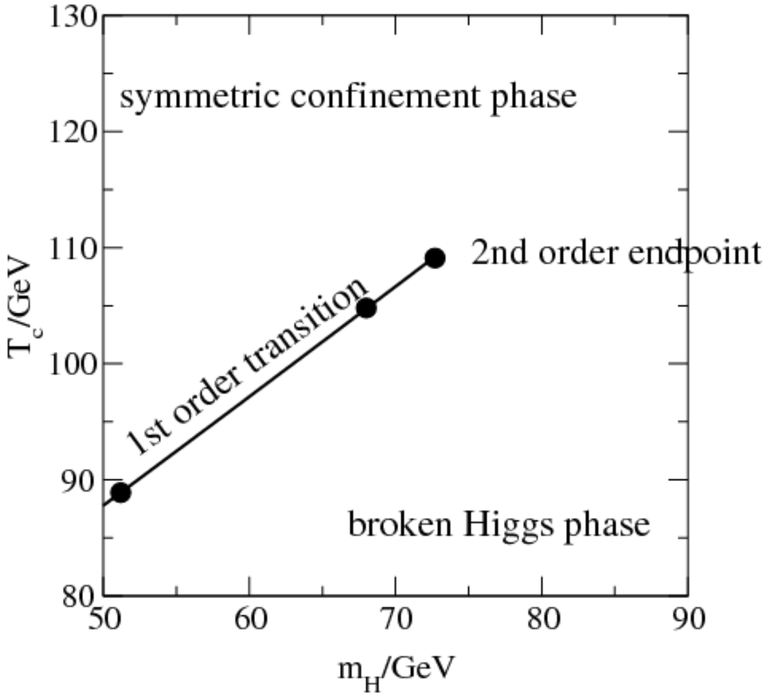
$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40 \text{ GeV}.$$

Is this the way the Standard Model generates the asymmetry ?

- It turns out that if the Higgs mass would have been lower than 70 GeV, the phase transition would have been first order



This has been extensively studied in the lattice

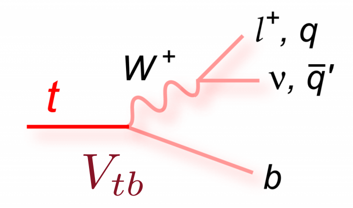
Kajantie et al'95

- But the Higgs mass is 125 GeV, and the electroweak phase transition is a simple cross-over transition. Making the phase transition strongly first order requires new physics.

CP Violation

- CP violation is induced by complex phases in the Yukawa interactions of quarks and leptons with the Higgs field. 3 Generations are necessary !

Kobayashi, Maskawa'73. 2008 Nobel Prize (together with Nambu)



$$M^f_{\rm diag} = V^f_L \; Y_f \; V^{f\dagger}_R \; \frac{v}{\sqrt{2}}$$

- It is always proportional to the so-called Jarlskog's invariants that is proportional to the mixing angles appearing in W interactions…

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V^u_L V^{d\dagger}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$J = c_{12}c_{13}^2 s_{12}s_{13}s_{23}\sin\delta$$

δ : CP violating phase

Does Nature uses this SM CP Violation ?

- In spite of the fact that CP-violation is the only apparent reason nature chose three generations, it does not seem to be used for baryogenesis.

- The baryon number generated at a phase transition would be several orders of magnitude lower than what is necessary.

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}}\frac{\alpha_W T}{32\sqrt{\alpha_s}}\right]^3 J\,\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\,\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

Gavela, Hernandez, Orloff, Pene, Quimbay'94

- In the quark sector, .

$$J = 3\times 10^{-5},\ \gamma \simeq 100\ \mathrm{GeV}$$

- New sources of CP violation are necessary.

Preservation of the Baryon Asymmetry

- EW Baryogenesis would be possible in the presence of new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario. Huet, Nelson '91; Giudice '91, Espinosa, Quiros,Zwirner '93.

- Relevant SUSY particle: Superpartner of the top

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

Carena, Quiros, C.W.'96, Delepine et al'96, Cline et al'99, Huber and Schmidt'00, Carena, Quiros, Nardini, C.W.'09, Cirigliano et al'09, Cohen et al'12, Curtin et al'12

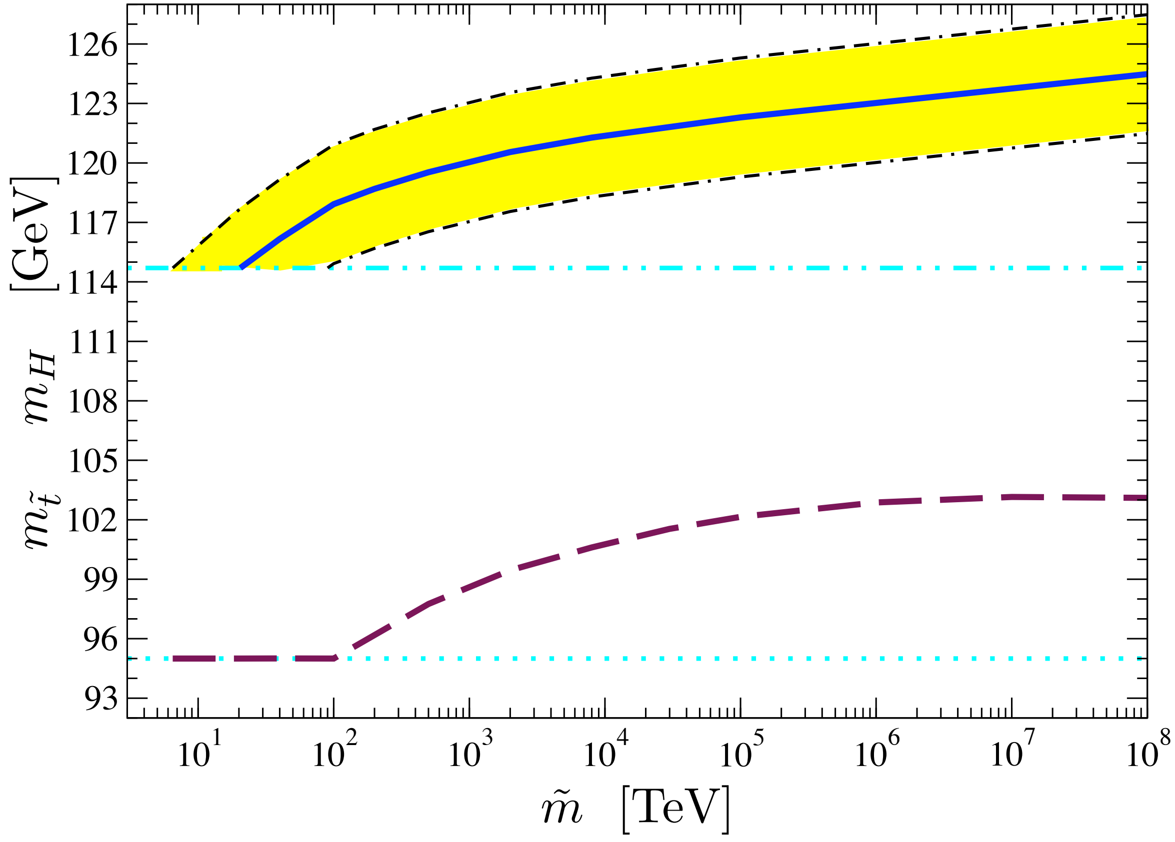
- Since $\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda}$, with $\lambda \propto \frac{m_H^2}{v^2}$

Higgs masses up to 120 GeV may be accomodated

Upper Bound on the Higgs Mass. Largest values of At

M. Carena, G. Nardini, M. Quiros, C.W. '08

$$m_Q = m_{\tilde{q}} = m_A = m_{\tilde{l}} = \tilde{m}$$



Computation using renormalization group improved Higgs and stops effective potentials

Both the Higgs and the lightest stop must be lighter than about 125 GeV for the mechanism to work. Values of the Higgs mass above 120 GeV may only be obtained for very large values of $\tilde{m}$.

Comments

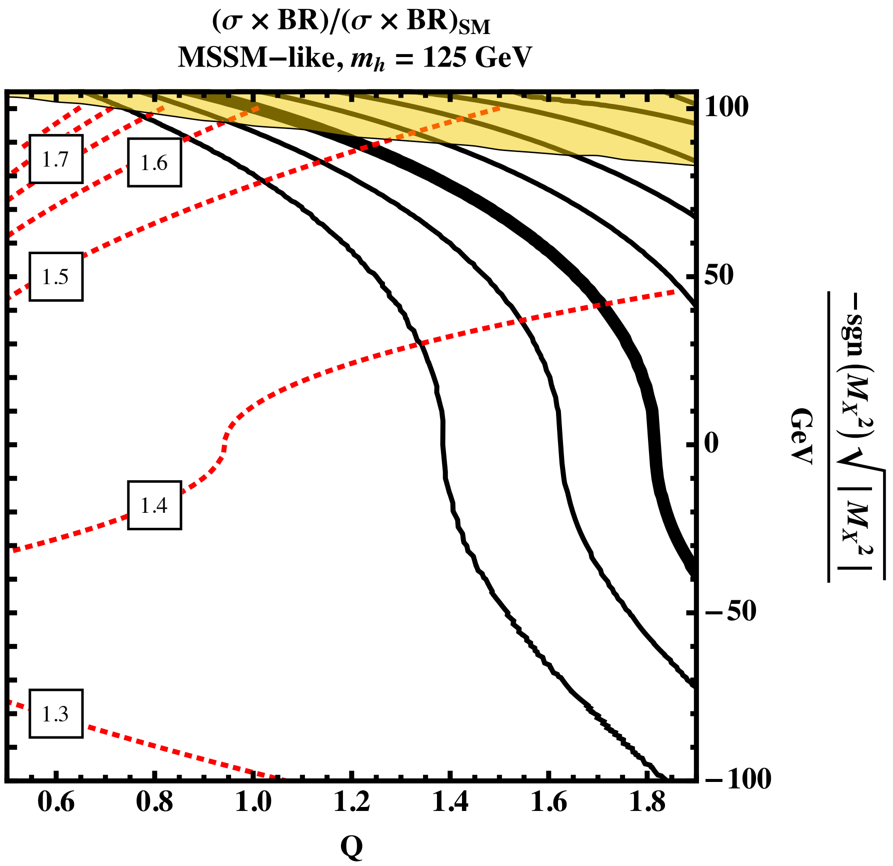
- The large values of the heavy squark masses render the model unnatural.

- Observe, however, that these particles have nothing to do with the EWPT or with the mechanism of baryogenesis and are heavy only to ensure the heaviness of the Higgs

- One can imagine a model with a singlet where the Higgs mass is lifted for relatively small values of tan(beta) and lighter heavy stops, with masses of order of a TeV.

- One should therefore analyze the phenomenological constraints concentrating on the light Higgs, stops and eventually netralinos.

For light stops, there is an enhancement of a factor of about 2 to 3 in the gluon fusion diagram, (Menon-Morrissey '09)



Cohen, Morrissey, Pierce'12
Curtin, Jaiswal, Meade'12

$$\Gamma_{gg} = \frac{\alpha_s^2}{128\,\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i g_i\,T_2^i\,F_{s_i}(\tau_i)\right|^2$$

$$-\mathscr{L} \supset M_X^2|X|^2 + \frac{K}{6}|X|^4 + Q|X|^2|H|^2,$$

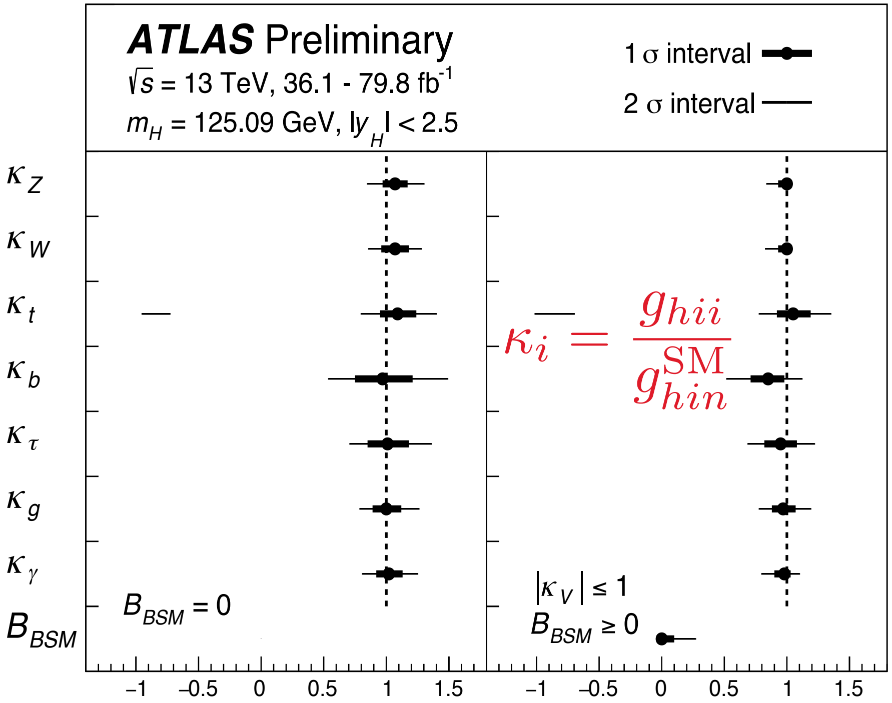
Generic Problem for models with light colored scalars

Is the Higgs the SM one ?

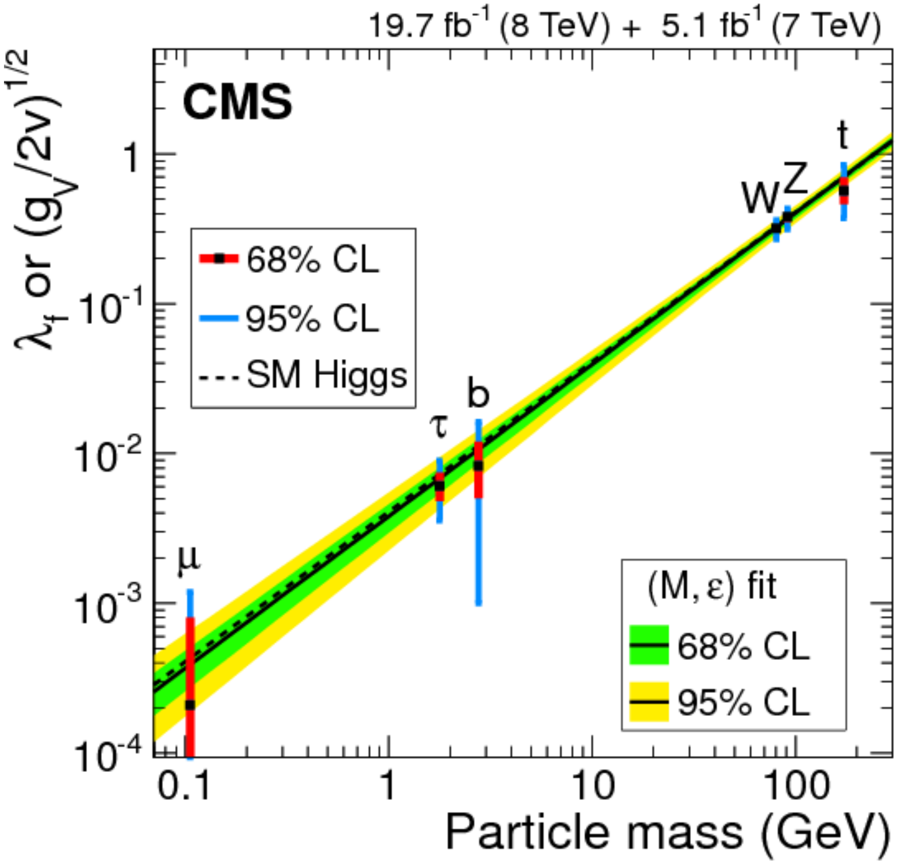
Linear correlation of masses and Higgs couplings established.
Another Standard Model triumph

Agreement at the 20 percent level :

$$g_{HPP} \propto \frac{m_P}{v}$$



$$\kappa_i = \frac{g_{hii}}{g_{hin}^{\rm SM}}$$



Models with light colored scalars seem
to be ruled out by Higgs physics.

Possible way out, has been ruled out

Carena, Nardini, Quiros, C.W.'13

Simple Alternatives to the light Stop Scenario

- Many models were written. There are nice reviews, for instance,
  Cohen, Kaplan, Nelson'93, Troden'98, D.E. Morrissey and J. Ramsey-Musolf, 1206.2942
- One important alternative is to introduce particles with no charges or only electroweak charges. In the simple models there are simply Higgs particles.
- Higgs particles can affect the potential at the thermal level, via E terms, but most importantly can modify the potential via mixing with the SM Higgs.
- If these new particles are heavy, they can be integrated out and they may be studied via an effective potential analysis.
- Potential is modified even at zero temperature, and hence the minimal signature is a modification of the Higgs self interactions.
- If they are light, they tend to affect the potential in a complex way, and one requires a numerical analysis to determine the nature of the electroweak phase transition.

Generic potential with non-renormalizable operators

Menon et al’04, Grojean et al’04, Nobel et al’08

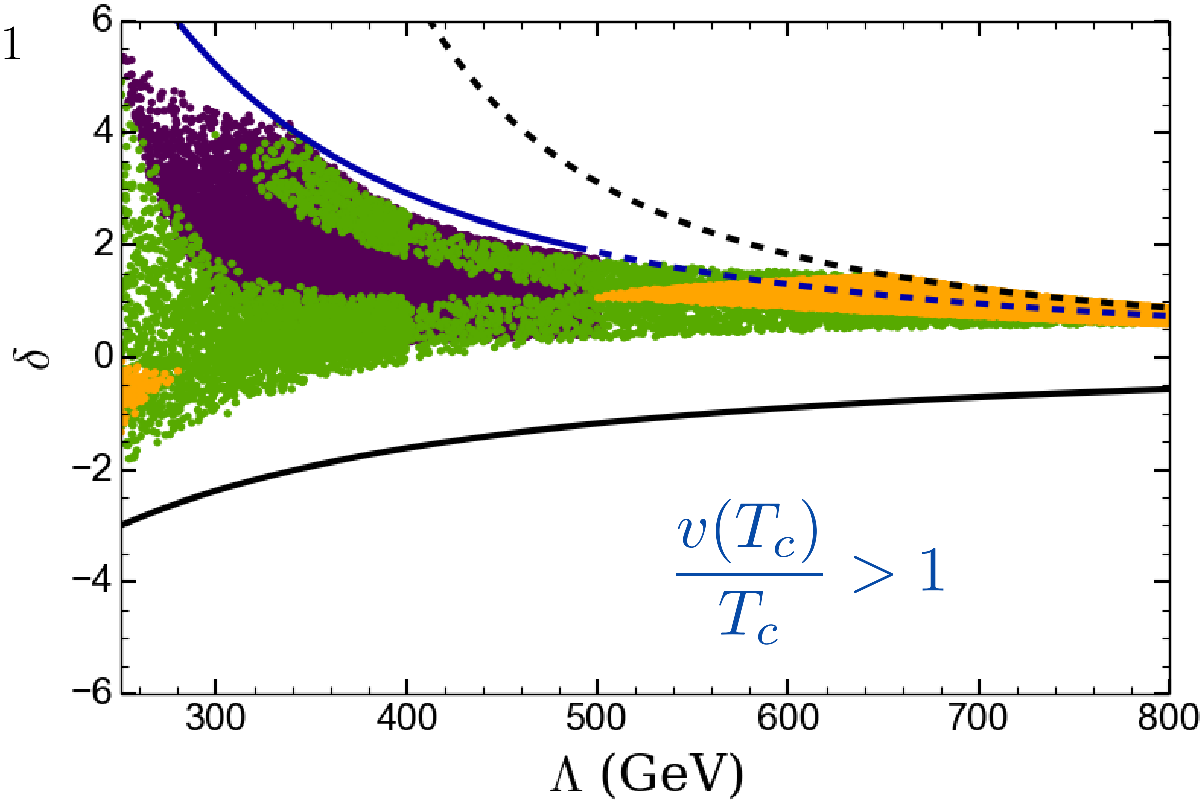
$$V\left(\phi,0\right) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^4 + \sum_{n=1}^{\infty}\frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}}\left(\phi^\dagger\phi\right)^{n+2}$$

$$\frac{c_H}{8\Lambda^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

One of the relevant characteristics of this model is that the self interactions of the Higgs are drastically modified.

Joglekar, Huang, Li, C.W.’15

$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1$$

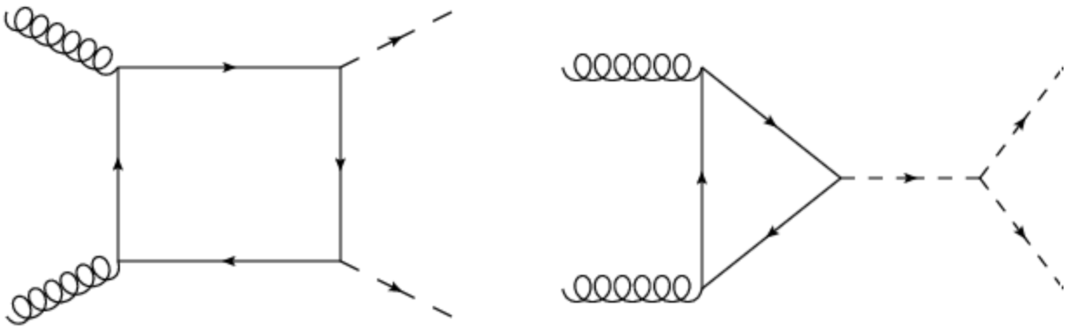


$$\lambda_3 = \frac{3m_H^2}{v}\left(1 + c_6\frac{2v^4}{m_h^2\Lambda^2} - \frac{3}{2}c_H\frac{v^2}{\Lambda^2}\right)$$

Corrections in the potential up to $(\phi^\dagger\phi)^5$

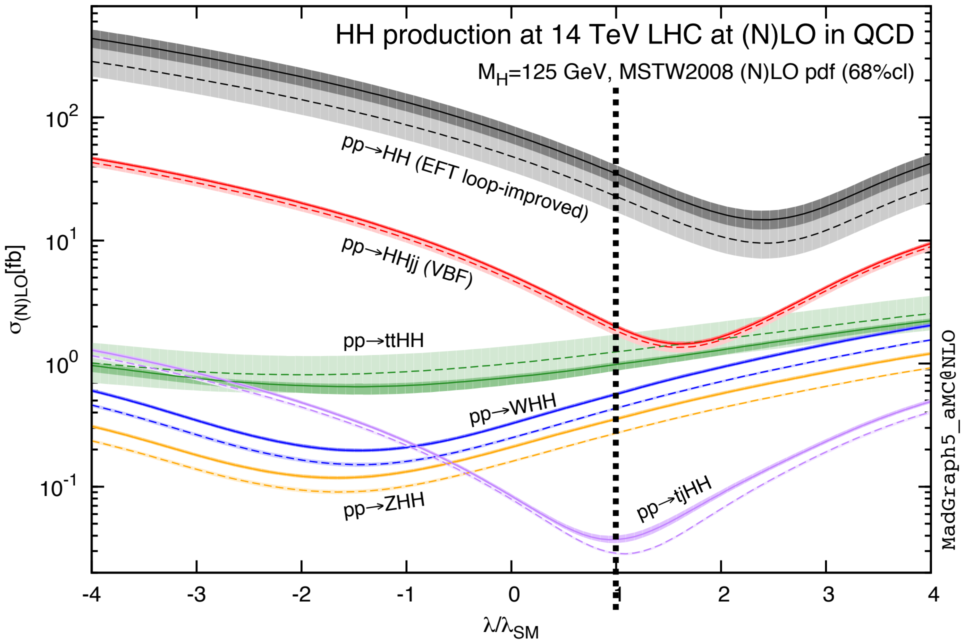
Main signature : New bosons or fermions at the weak scale (LHC)

Additional Signature : Higgs Potential Modification
Variation of the trilinear Higgs Coupling



Double Higgs Production

Frederix et al'14



Curtin et al'14
Joglekar, Huang, Li, C.W. 1512.00068,
Huang, Long, Wang 1608.06619,
Carena, Liu, Rimbeau 1801.00794

We will start to probe this scenario at the HL-LHC, but only a higher energy collider will lead to a definite answer

P. Bokan'17

Limits on the cross-section as a function of κ_λ

$4b$

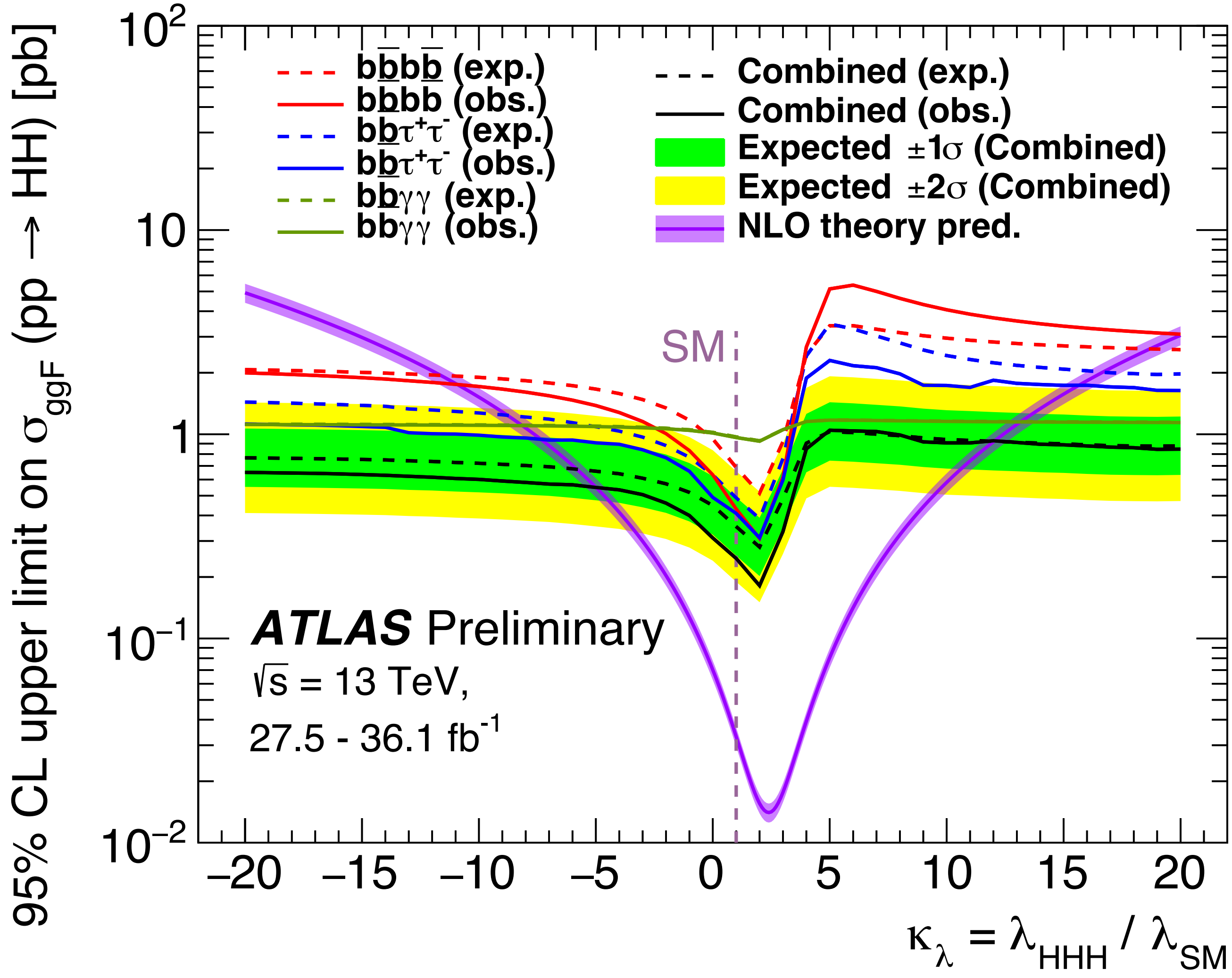
$bb\tau\tau$

$bb\gamma\gamma$

combination

dashed:
expected

solid:
observed



The scale factor κ_λ is observed (expected) to be constrained in the range:

$$-5.0 < \kappa_\lambda < 12.1 \ (-5.8 < \kappa_\lambda < 12.0)$$

High Lumi LHC :

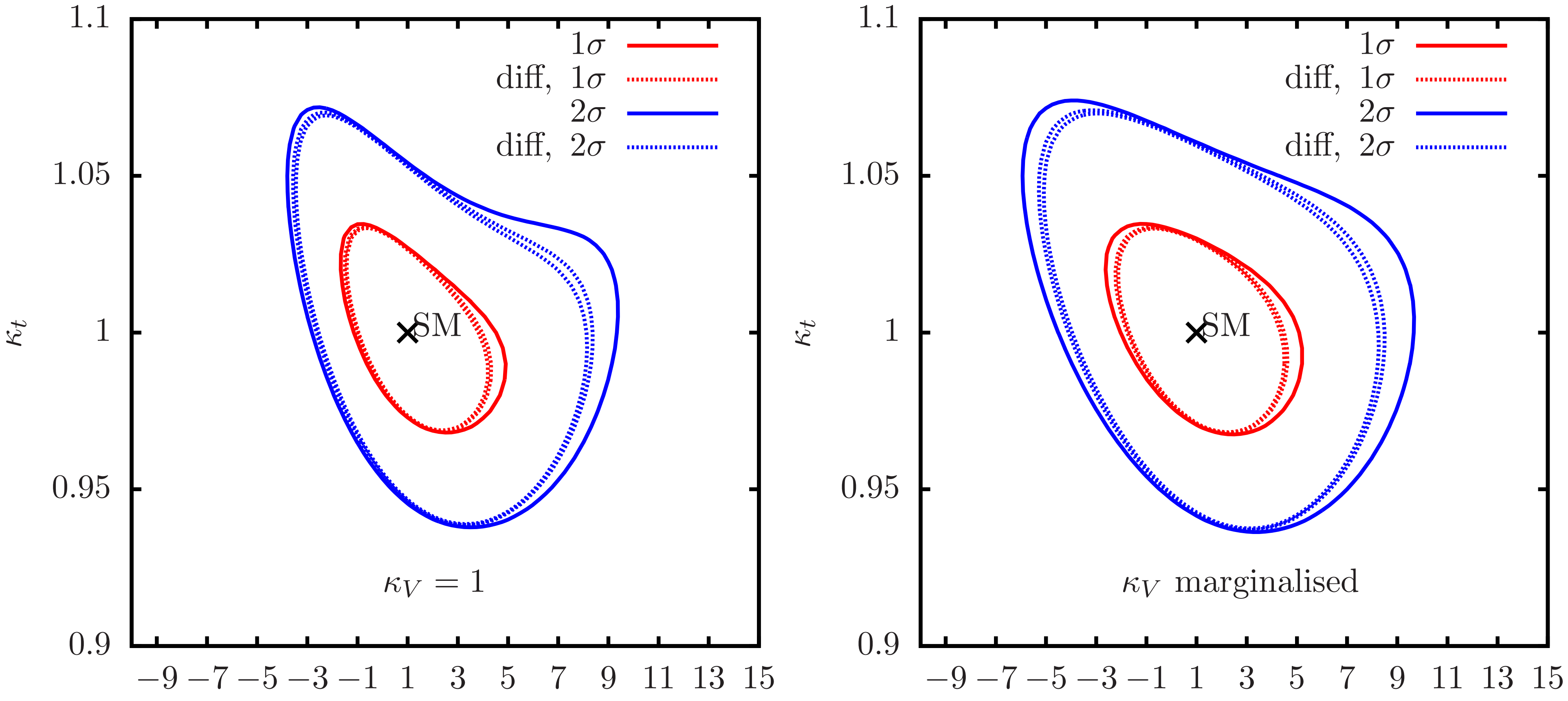
limit on κ_λ (for ATLAS with only yybb channel) :

D. Delgove'17

$0.2 < \kappa_\lambda < 6.9$

Putting everything together : Sensitivity at the high luminosity LHC

A. Shivaji'17



Explicit Models with light particles : Singlet Extension

Profumo, Ramsey Musolf, Wainwright, Winslow'14

$$V_0^{T=0}(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4. \qquad (2)$$

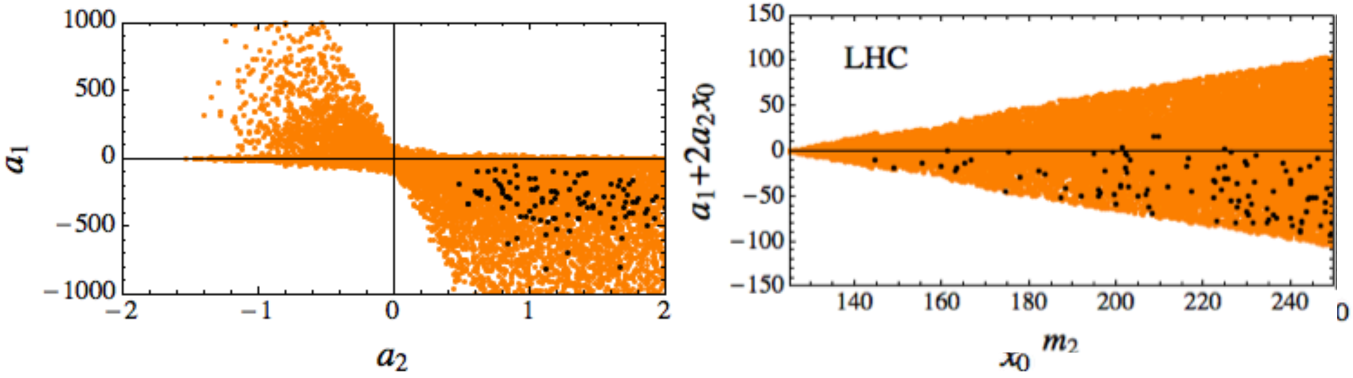
Bounds from precision measurement as well as from searches and requiring the nucleation to occur

$$m_{hh}^2 \equiv \frac{d^2V}{dh^2} = 2\lambda v_0^2$$

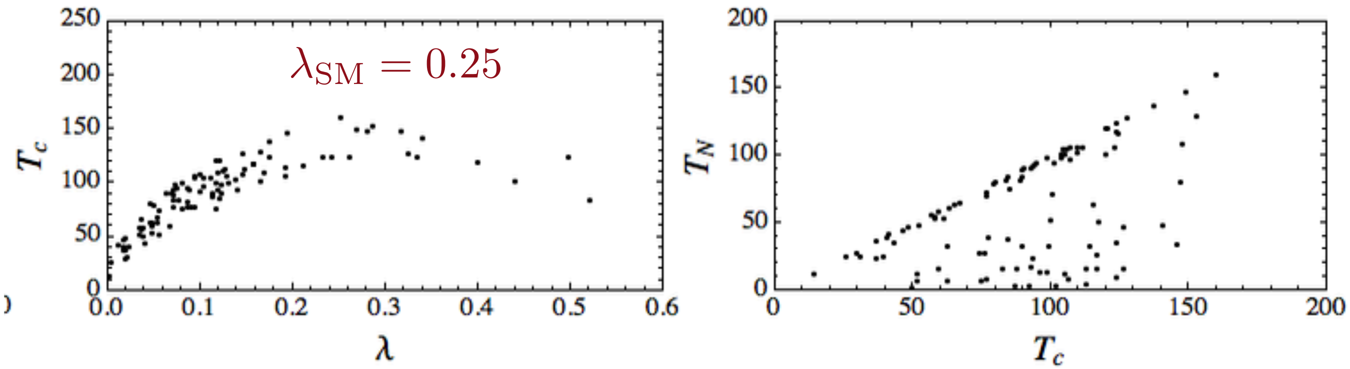
$$m_{ss}^2 \equiv \frac{d^2V}{ds^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

$$m_{hs}^2 \equiv \frac{d^2V}{dhds} = (a_1 + 2a_2 x_0)\frac{v_0}{2},$$

Correlation of parameters to make mixing small.



Nucleation temperature may be very different from transition température. Actually, if the barrier is large, nucleation may not occur.



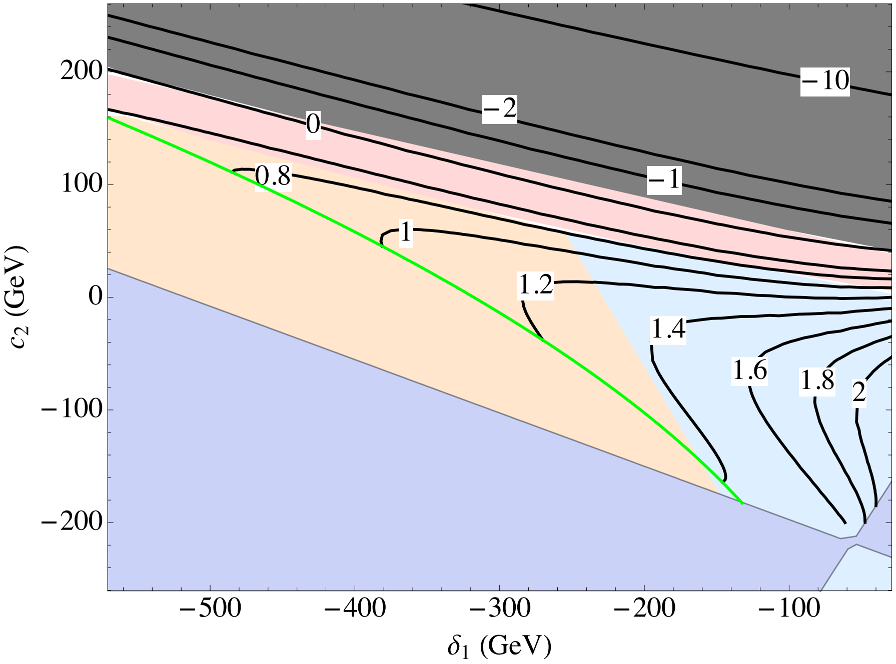
Non-trivial mixing allows λ to deviate from SM value

Related Study

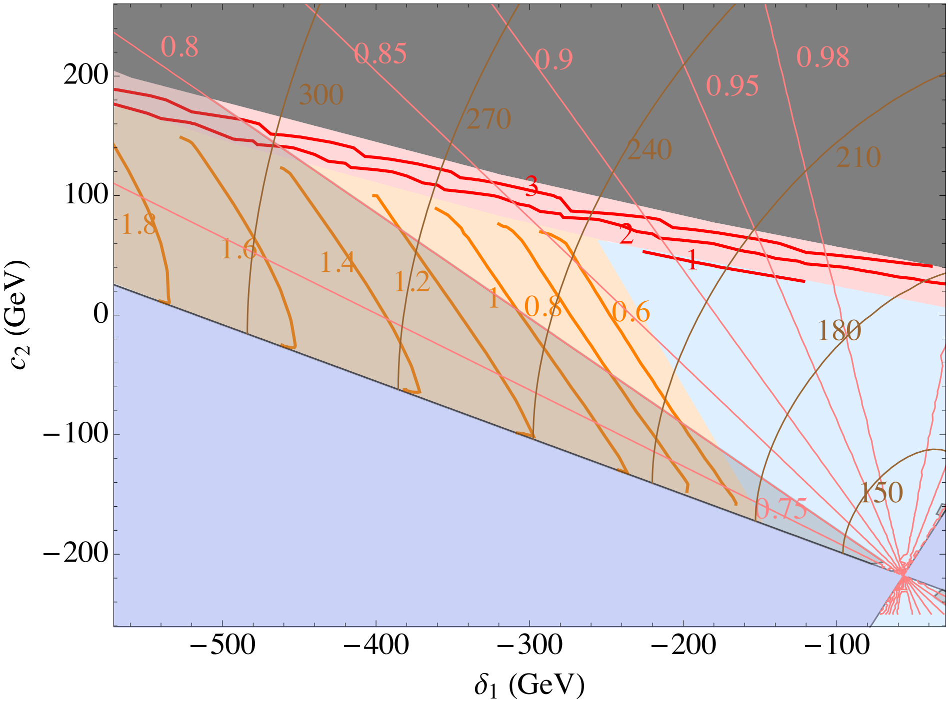
Bian, Jiang, Huang, Shu'18

$$\begin{aligned} V\left(H,\mathbb{S}\right) &= \frac{1}{2}m^2 H^\dagger H + \frac{\lambda}{4}\left(H^\dagger H\right)^2 + \frac{\delta_2}{2}H^\dagger H\left|\mathbb{S}\right|^2 \\ &+\left(\frac{\delta_1 e^{i\phi_{\delta_1}}}{4}H^\dagger H\mathbb{S} + \text{c.c.}\right) + \frac{b_2}{2}\left|\mathbb{S}\right|^2 + \frac{d_2}{4}\left|\mathbb{S}\right|^4 \\ &+\left(\frac{1}{4}b_1 e^{i\phi_{b1}}\mathbb{S}^2 + \frac{c_2 e^{i\phi_{c2}}}{6}\mathbb{S}\left|\mathbb{S}\right|^2 + \text{c.c.}\right), \qquad (4) \end{aligned}$$

Black Lines : $(V_S - V_H)/(10^8\text{GeV})^4$



Orange (1 step) and red (2 steps) regions : SFOPT, with counters of vc/Tc



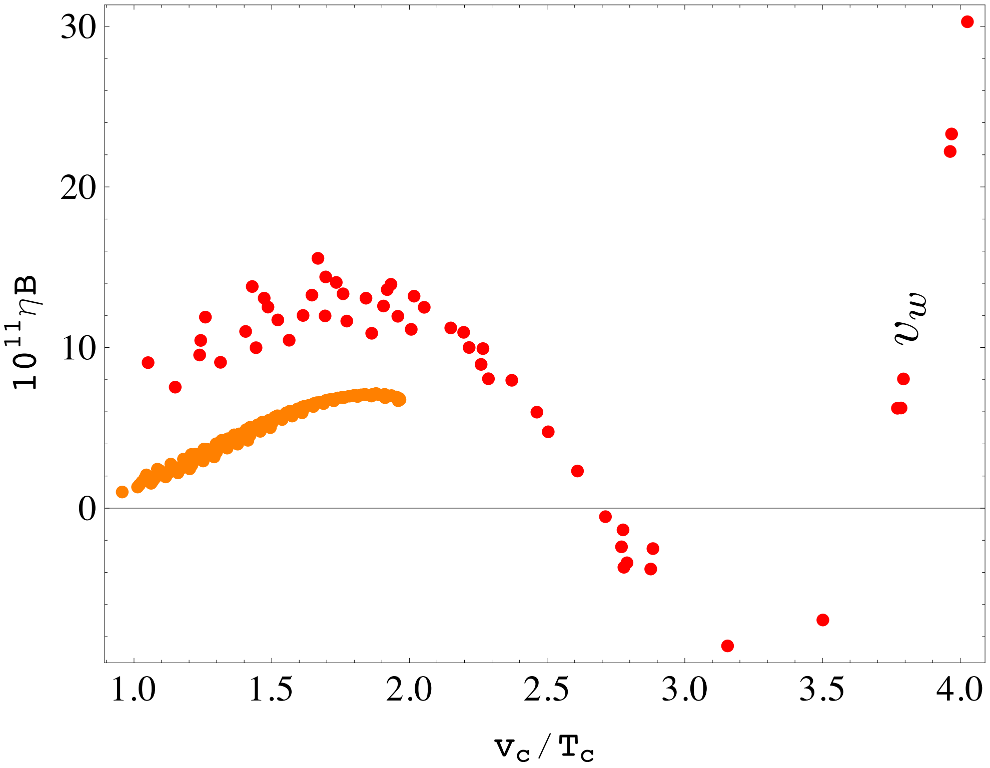
Generation of Baryon Asymmetry

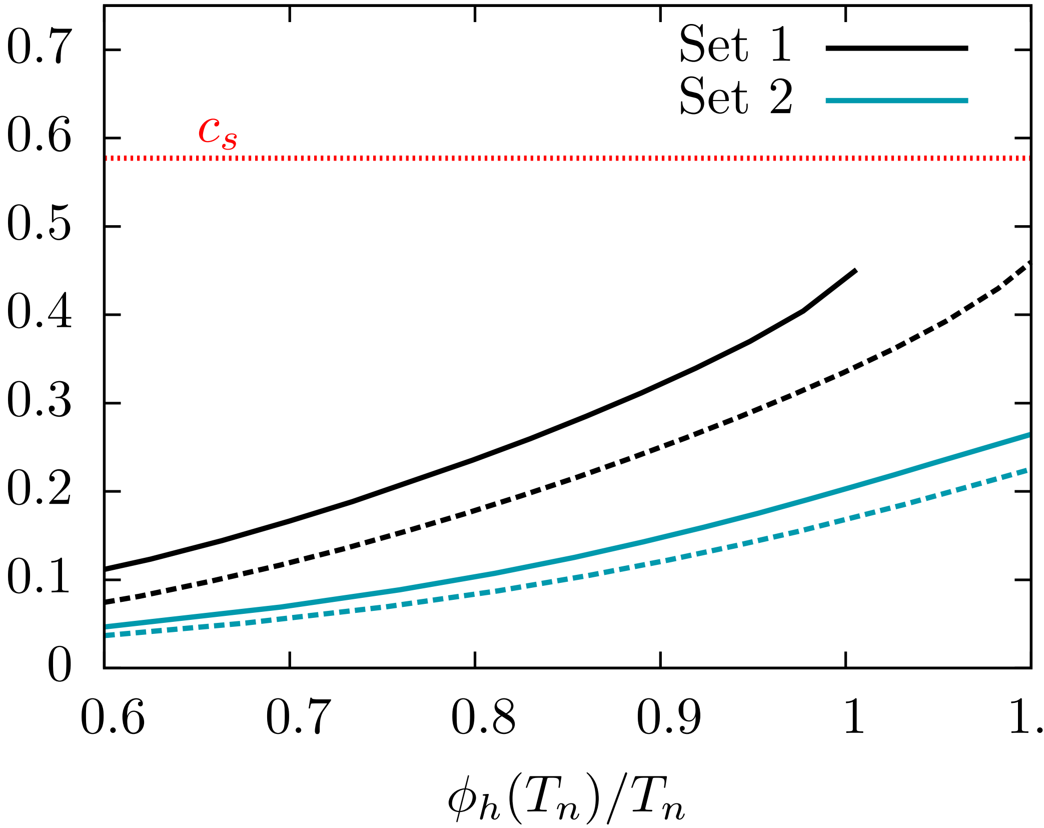
Kozaczuk'15

Bian, Jiang, Huang, Shu'18

$$y_t \bar{Q}_L H \left(1 + \frac{(a \ + ib)}{\Lambda^2} \mathbb{S}\mathbb{S}^\dagger\right) t_R + \text{h.c.}$$

Wall velocities tend to be larger than standard assumptions (0.01–0.05), demanding larger CP violating sources





Proper values appear naturally, by serendipity

Z_2 Preserving Case

Example: Singlet Extension of the SM

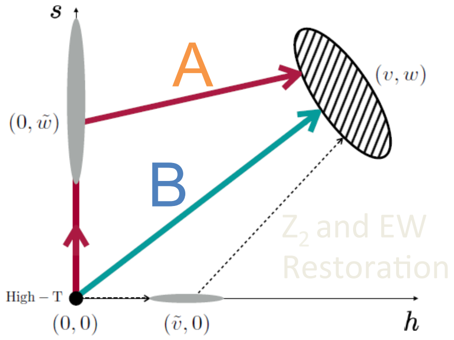
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

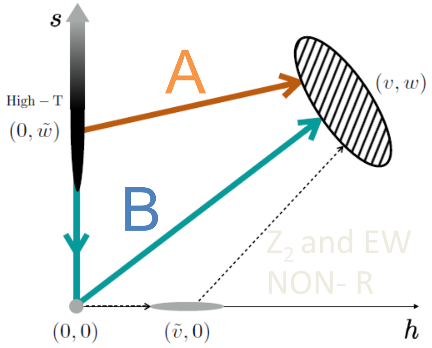
+ ~~Z_2 breaking terms~~

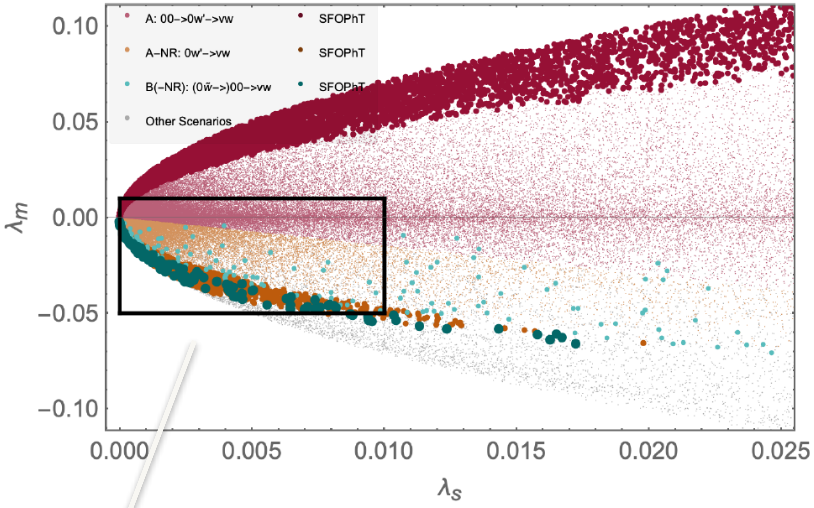
Spontaneous Z_2 extension specially motived by its connection to dark sector physics

- Non-Standard, rich thermal histories allow for additional phase transitions at higher temperatures and yield a strong SFOPhT

Carena, Wang, Liu'19





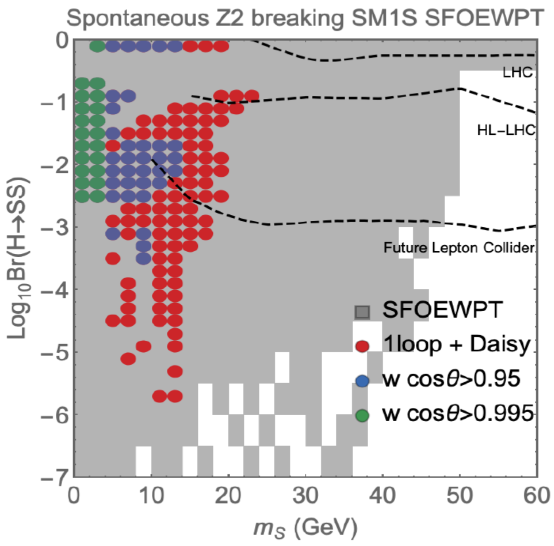


Points inside the rectangle compatible with current bounds on Higgs exotic decays

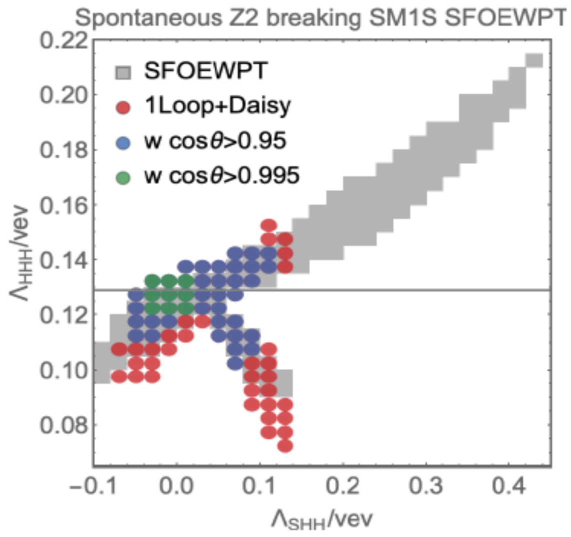
Singlet Extension of the SM with Spontaneous Z2 breaking

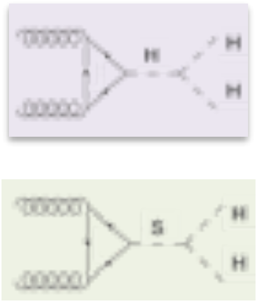
Exciting Phenomenology (important effects of high order corrections to the potential)

Higgs Exotic Decay



Double Higgs Production





- **A firm prediction of a light scalar**
- **Dashed lines: sensitivity to** H → SS → 4j
- Higgs exotic decay into light scalars is a crucial probe that requires further studies of **merged jets** for lighter singlet masses

- Higgs trilinear coupling can be either enhanced or suppressed by O(30%)
- Double Higgs production at HL-LHC & FCC-hh provides insights for this mode

Carena, Lui, Wang'19

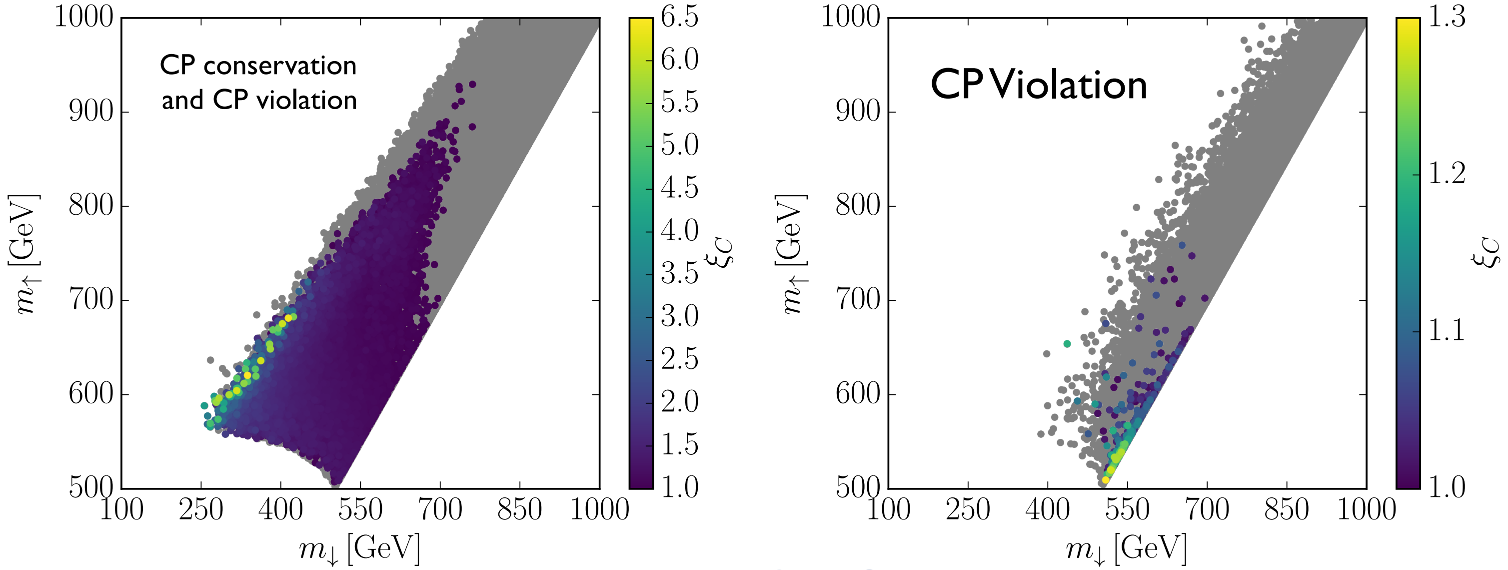
Adding Doublets

Basler, Mühlleitner and Wittbrodt'17

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] .$$

$$V_{\text{CW}}(\{\omega\}) = \sum_i \frac{n_i}{64\pi^2} (-1)^{2s_i} \, m_i^4(\{\omega\}) \left[\log\left(\frac{m_i^2(\{\omega\})}{\mu^2} \right) - c_i \right] . \qquad V^T = \sum_k n_k \frac{T^4}{2\pi^2} J_\pm^{(k)}$$

Type II : Heavy Higgs tends to decay into top pairs, unless the channel H3 to H2 Z is open

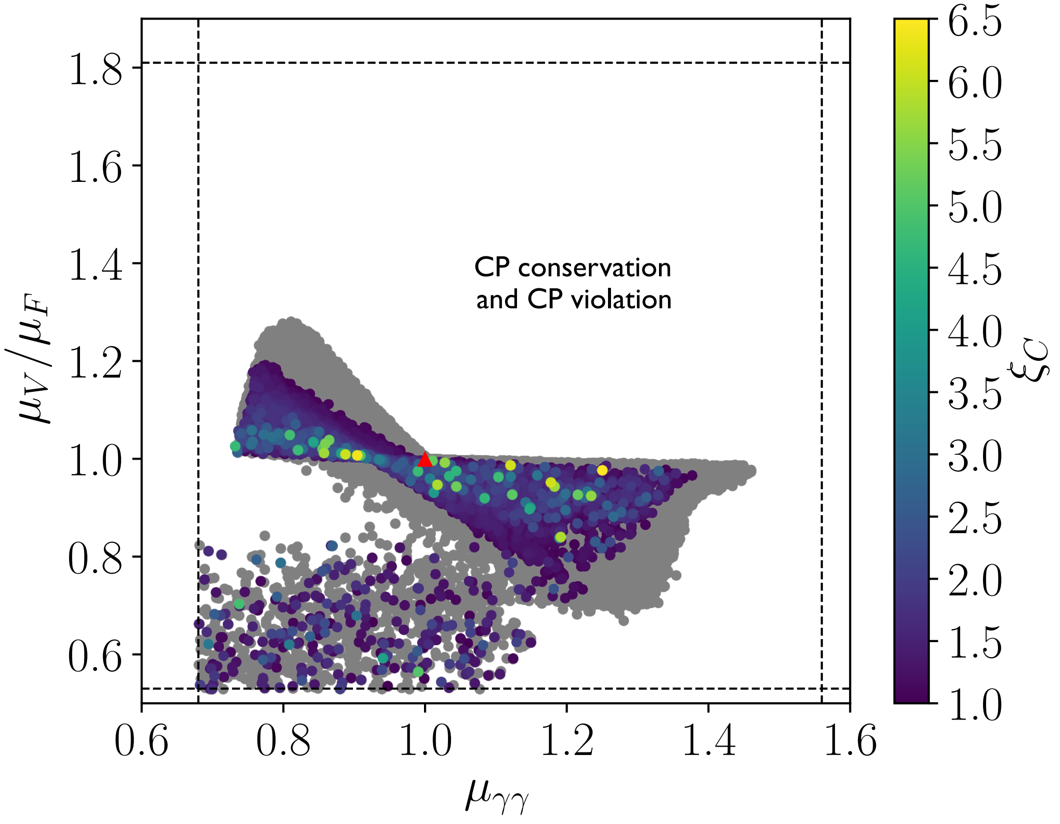


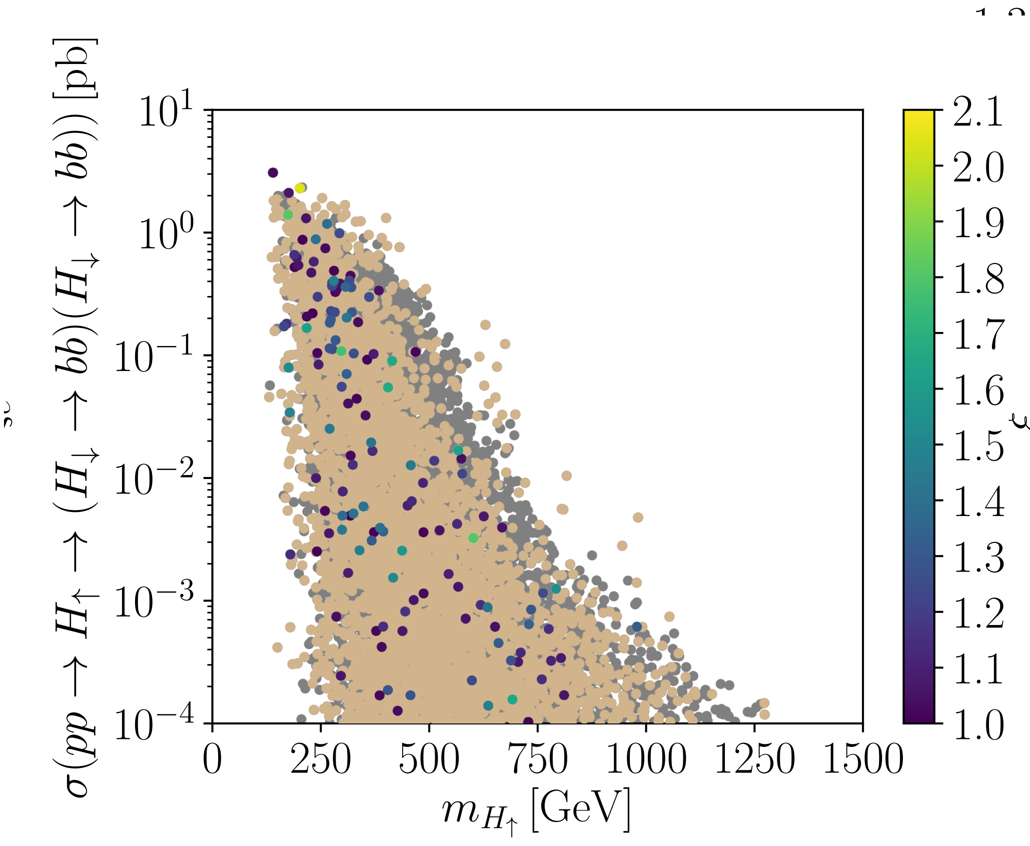
Difference is mostly statistics

Blue : SFOPT

Large quartic couplings tend to induce large mixings and non-standard phenomenology

Basler, Mühlleitner and Wittbrodt'17





Higgs Precision Measurements is already constraining a large region of parameter space where this scenario is viable.

Resonant Higgs production may be relevant in certain regions of parameter space. Parameter space somewhat surprising.

Supersymmetric Models of Electroweak Baryogengesis

- They are characterized by the appearance of a barrier between the rival and physical minima at either zero or finite temperature.

- Generation of barriers at finite temperature need the presence of light particles strongly coupled to the Higgs and are therefore constrained by the LHC. One example is the light stop scenario, which is currently ruled out

  Carena, Quiros, C.W.'96, Delepine et al'96, Cline et al'99, Huber and Schmidt'00,
  Carena, Quiros, Nardini, C.W.'09, Cirigliano et al'09, Cohen et al'12, Curtin et al'12

- There are models also with heavy fermions. Megevand et al'04, Fok et al'07,Katz et al'14

- Models with barriers at zero temperature have the advantage that need only weakly coupled particles, but a possible problem is that the barrier prevents the transition, even if the physical minimum is the deeper one.

  Pietroni'93, Davies et al'96, Huber et al'00,
  Menon et al'04, Carena et al'12,
  Profumo et al'14, Kosaczuk et al'15,
  Athorn et al'19, Baum et al, to appear

Carena, Haber, Low, Shah, C.W.'15

Naturalness and Alignment in the NMSSM

see also Kang, Li, Li,Liu, Shu'13, Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to λ_4)

$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta + \delta_{\tilde{t}} \right)$$

$$\delta\tilde{\lambda}_3 = \lambda^2$$

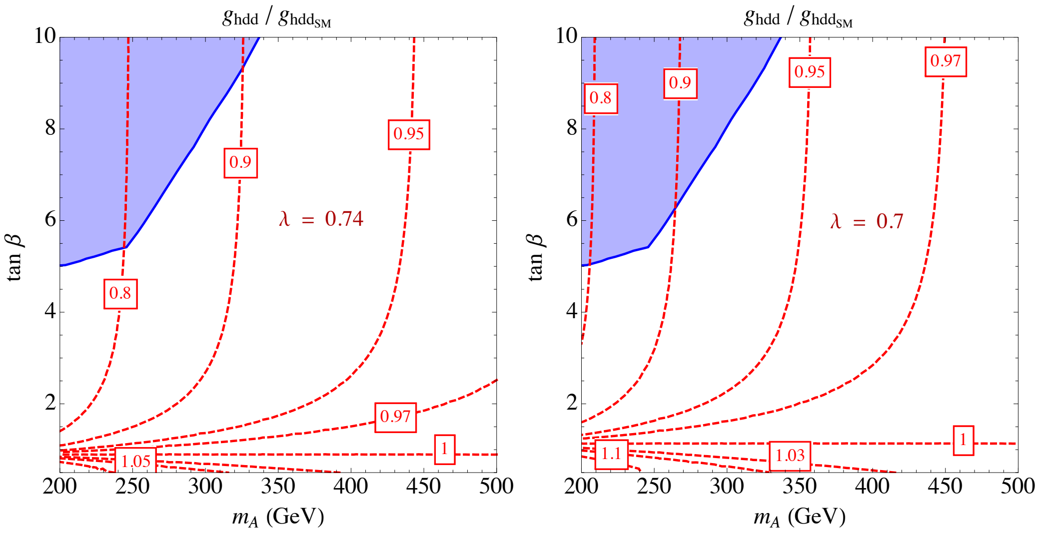
- The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of $\tan\beta$

- The values of end up in a very narrow range, between 0.65 and 0.7 for all values of tan(beta), that λ are the values that lead to naturalness with perturbativity up to the GUT scale

$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta}$$

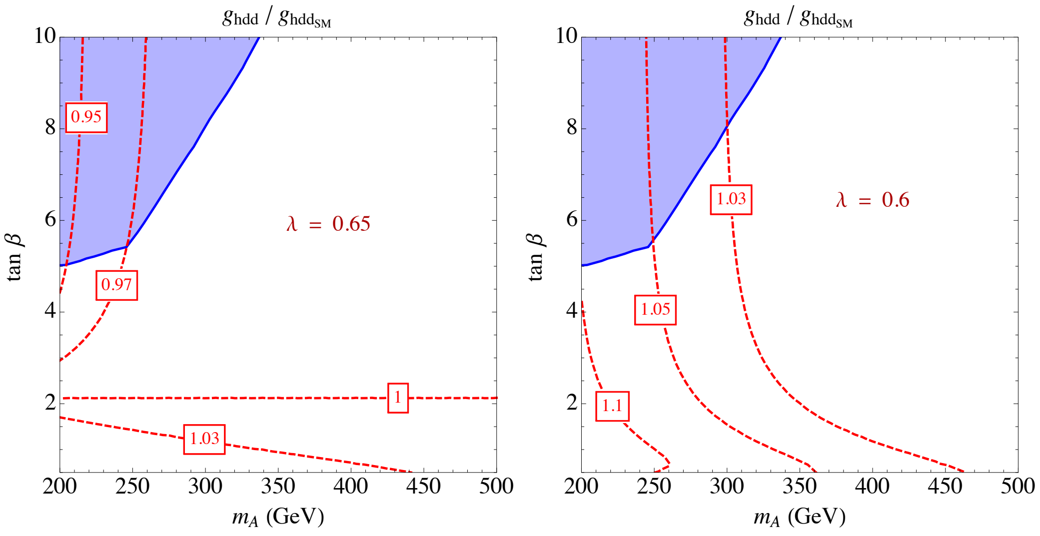
Alignment in the NMSSM (heavy or Aligned singlets)

Carena, Low, Shah, C.W.'13



(iii)

(iv)



It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided λ is about 0.65

Aligning the CP-even Singlets

Carena, Haber, Low, Shah, C.W.'15

- The previous formulae assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states
- The mixing mass matrix element between the singlets and the SM-like Higgs is approximately given by

$$M_S^2(1,3) \simeq 2\lambda v\mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

- If one assumes alignment, the expression inside the bracket must cancel
- If one assumes $\tan\beta < 3$ and lambda of order 0.65, and in addition one asks for kappa in the perturbative regime, one immediately conclude that in order to get small mixing in the Higgs sector, the CP-odd Higgs is correlated in mass with the parameter μ
- Since both of them small is a measure of naturalness, we see again that alignment and naturalness come together in a beautiful way in the NMSSM
- Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets (and singlino) become self consistently light

Baum, Carena, Shah, C.W.'17

Phase Transition in the NMSSM close to Alignment

[Pietroni '92; Davies *et al.* '96; Huber+Schmidt '00; Menon *et al.* '04; ...]
Carena, Shah,C.W'12, Huang et al '14, Shu et al'15, Kozaczuk et al '15…

- The tree-level potential reads

$$\begin{aligned} V(H_u, H_d, S) \;&=\; -2\lambda S A_\lambda H_d H_u + \frac{2}{3}\kappa S^3 A_\kappa + \frac{1}{8}\left(g_1^2 + g_2^2\right)\left(H_u^2 - H_d^2\right)^2 + \left(kS^2 - \lambda H_d H_u\right)^2 \\ &+\; H_d^2 m_d^2 + \lambda^2 S^2\left(H_d^2 + H_u^2\right) + H_u^2 m_u^2 + m_2^2 S^2 \qquad (2.4) \end{aligned}$$

- The parameter are related to physical parameters by $\lambda < S >= \mu$ and

$$M_A^2 \;=\; \frac{2\mu\left(A_\lambda + \kappa\mu/\lambda\right)}{\sin(2\beta)}$$

- It is useful to go to the Higgs basis and decouple the heavy degrees of freedom

$$\begin{aligned} H_d &= \begin{pmatrix} \frac{1}{\sqrt{2}}\left(c_\beta H^{\mathrm{SM}} - s_\beta H^{\mathrm{NSM}}\right) + \frac{i}{\sqrt{2}}\left(-c_\beta G^0 + s_\beta A^{\mathrm{NSM}}\right) \\ -c_\beta G^- + s_\beta H^- \end{pmatrix} , \\ H_u &= \begin{pmatrix} s_\beta G^+ + c_\beta H^+ \\ \frac{1}{\sqrt{2}}\left(s_\beta H^{\mathrm{SM}} + c_\beta H^{\mathrm{NSM}}\right) + \frac{i}{\sqrt{2}}\left(s_\beta G^0 + c_\beta A^{\mathrm{NSM}}\right) \end{pmatrix} , \\ S &= \frac{1}{\sqrt{2}}\left(H^{\mathrm{S}} + iA^{\mathrm{S}}\right) . \end{aligned}$$

Effective Potential

S. Baum, M. Carena, N. Shah, Y. Wang, C.W., to appear

$$V_0^{\rm eff} = V_0 + \frac{\Delta\lambda_2}{2}\,|H_u|^4 \ .$$

We decouple the stops and include their associated radiative corrections, necessary to get the right Higgs mass. At one loop they are given by

$$\Delta\lambda_2 = \frac{3}{8\pi^2} h_t^4 \left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{A_t^2}{M_S^2}\left(1 - \frac{A_t^2}{12 M_S^2}\right)\right]$$

All other light particle one loop corrections included

$$V_{1-\rm loop}^{\rm CW} = \frac{1}{64\pi^2} \sum_{i=B,F} (-1)^{F_i} n_i \widehat{m}_i^4 \left[\log\left(\frac{\widehat{m}_i^2}{m_t^2}\right) - c_i\right]$$

At tree-level, the singlet potential and minima at alignment are given by

$$V_3^{\rm eff}(0,0,H^{\rm S}) \to -\kappa^2 \frac{\mu}{\lambda}\left(\frac{\mu}{\lambda} + \frac{A_\kappa}{2\kappa}\right)(H^{\rm S})^2 + \frac{\kappa A_\kappa}{3\sqrt{2}}(H^{\rm S})^3 + \frac{\kappa^2}{4}(H^{\rm S})^4$$

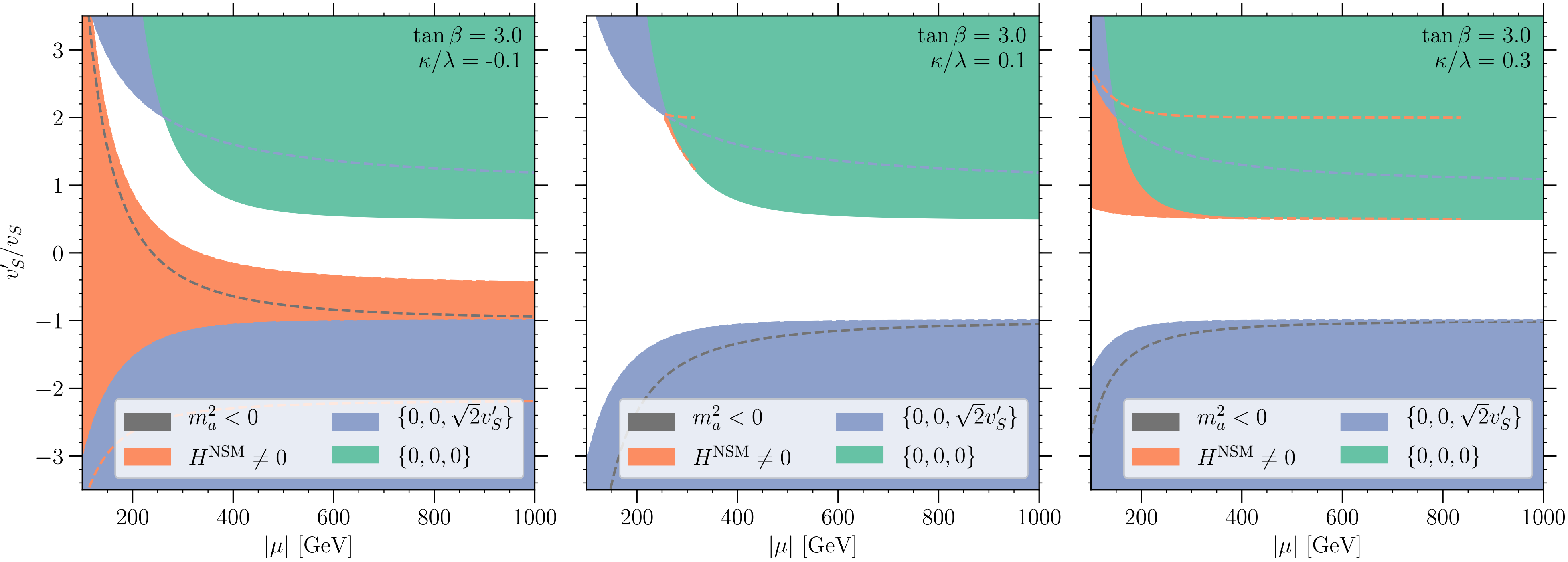
$$H^{\rm S} = \left\{0\,,\quad \frac{\sqrt{2}\mu}{\lambda}\,,\quad -\sqrt{2}\left(\frac{\mu}{\lambda} + \frac{A_\kappa}{2\kappa}\right)\right\}\ .$$

Allowed Region of Parameter Space

Baum, Carena, Shah, Wang, C.W., to appear

After alignment is imposed, relevant parameters are

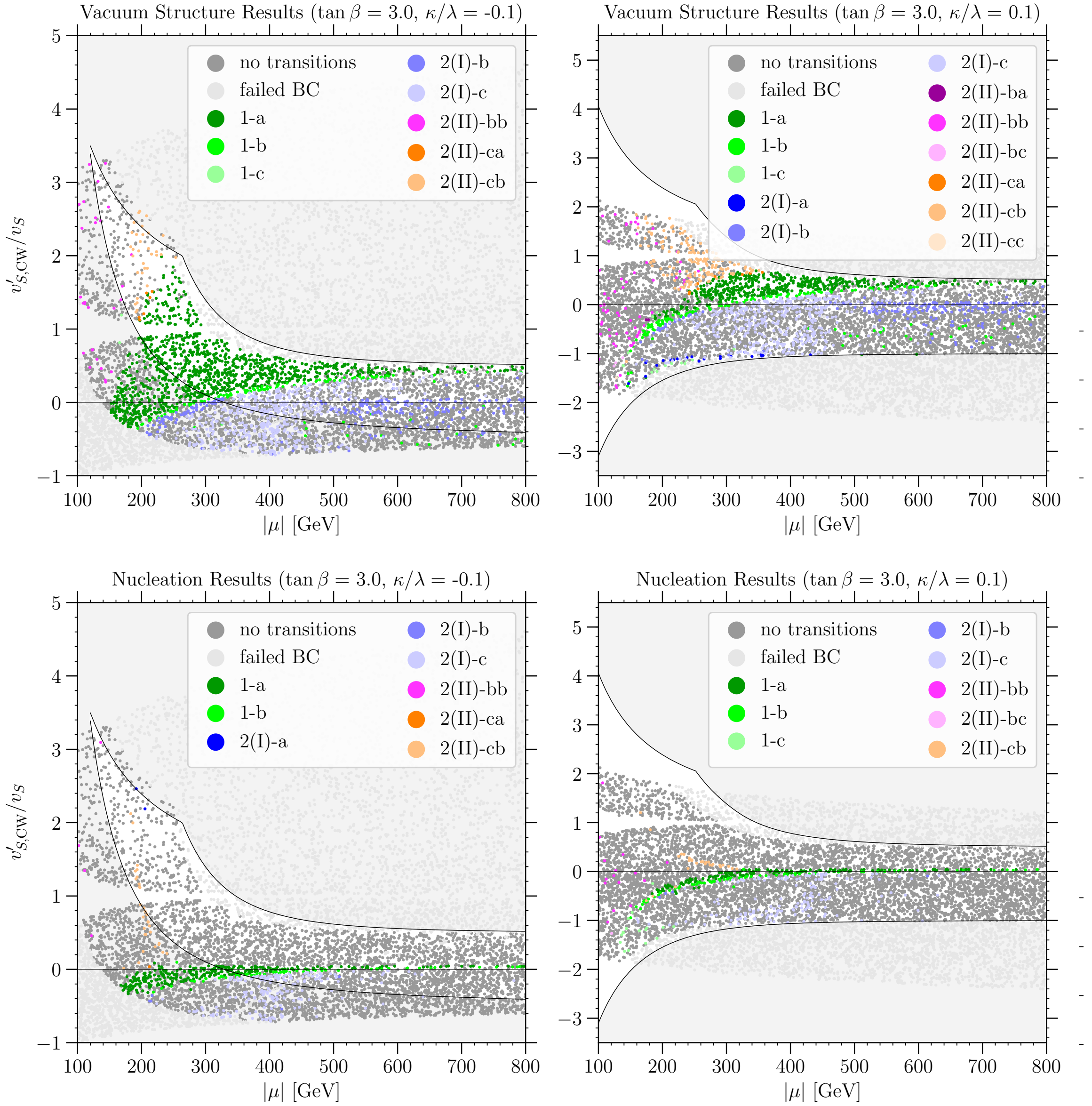
$$\tan\beta\,,\quad \mu\,,\quad \kappa\,,\quad A_\kappa$$



We replace A_κ/μ by $v'_S/v_S = -(1 + A_\kappa\lambda/(2\kappa\mu))$

Nucleation Results differ in a significant way from critical temperature ones

Baum, Carena, Shah, Wang, C.W., to appear



Displacement of allowed regions due to radiative corrections

Transition occurs mostly for small values of vs'/vs, for which barriers are small.

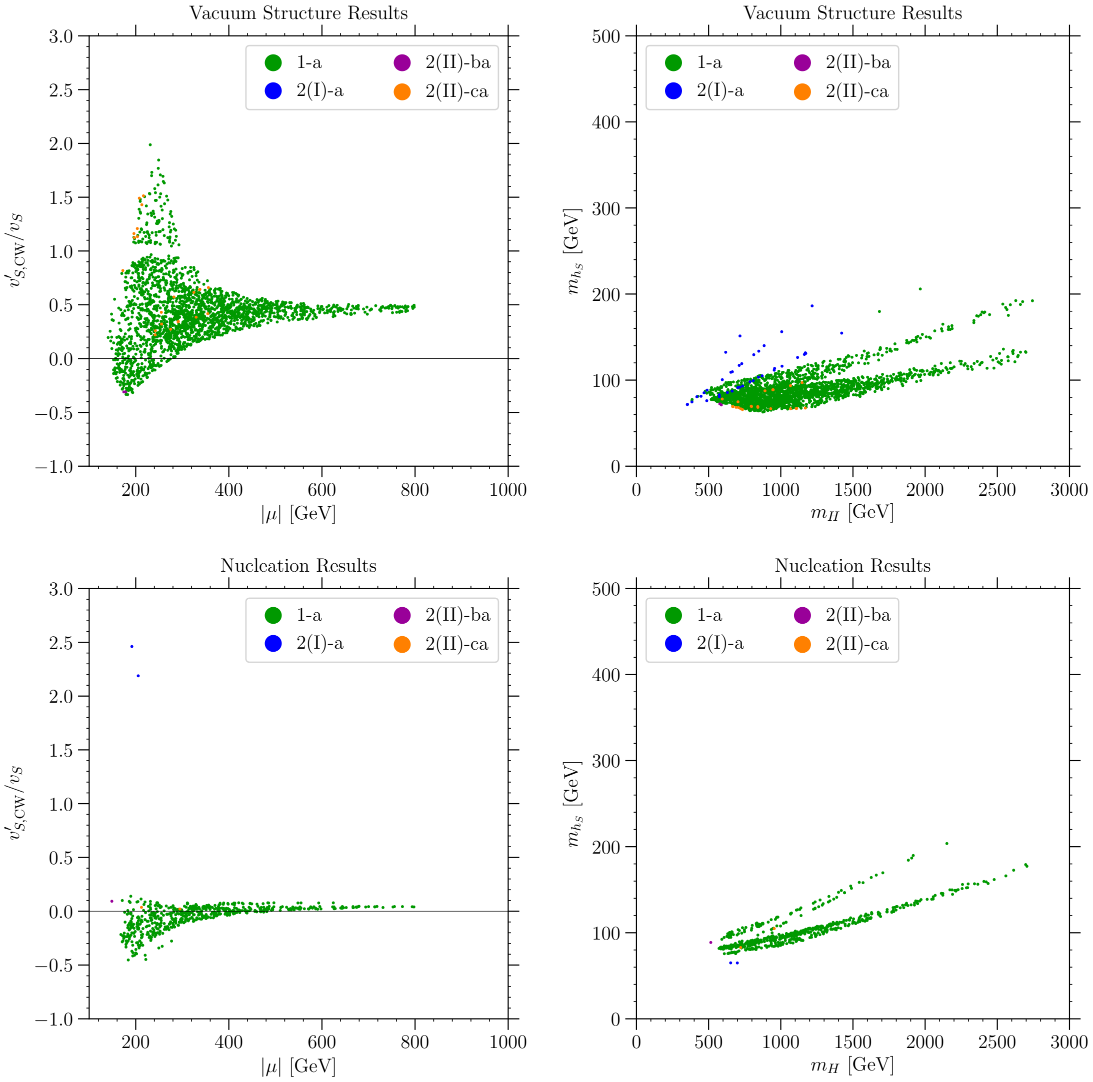
ΔV :

Not a good way of judging the phase transition pattern and strength

Higgs Mass Spectrum

Baum, Carena, Shah, Wang, C.W., to appear

At this values of tanβ, Higgs singlets tend to be light, but heavier than mh/2 and heavy Higgs bosons tend to be heavier than a few hundred GeV

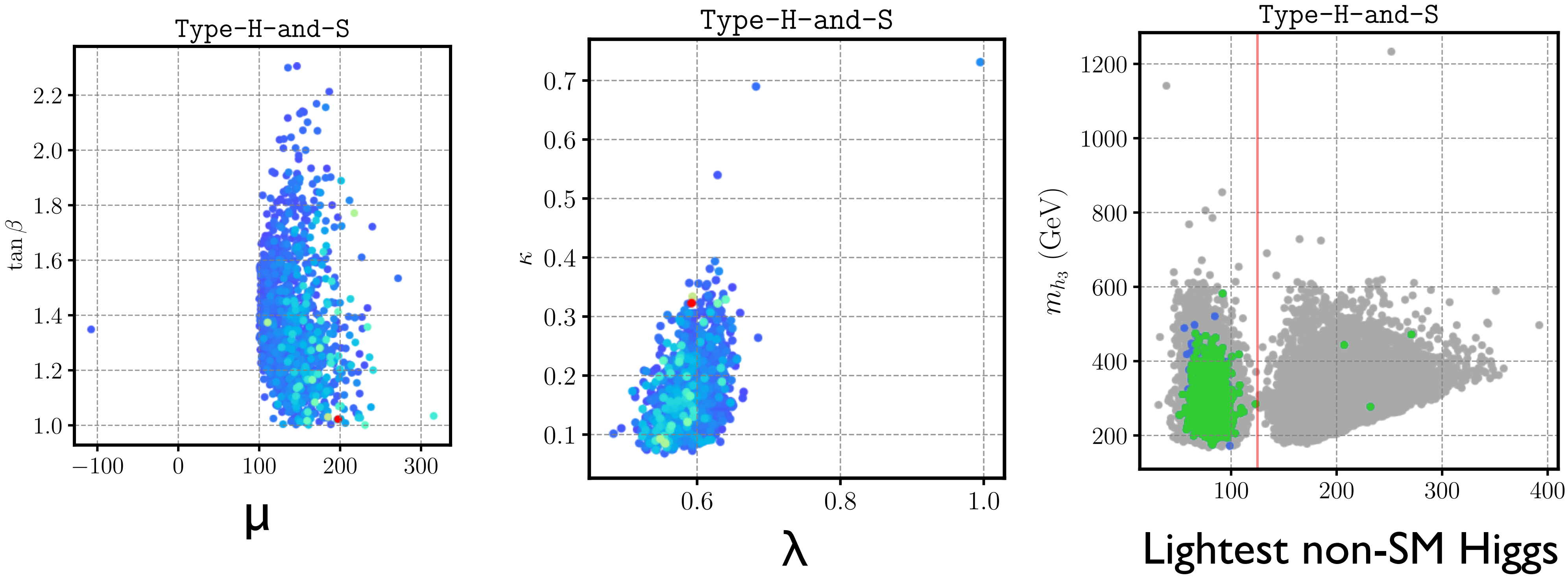


Important : Close to alignment,

$$m_A \simeq 2\mu/\sin(2\beta)$$

Results seem to differ from recent study of NMSSM via vacuum structure

Athron, Balazs, Fowlie, Pozzo, White, Zhang'19



Discrepancy may be related to statistics, due to our imposition of alignment, and our choice of tanβ.

We are now studying lower values of tanβ. Differences are intriguing. Difference due to nucleation will remain

Choice of CP-violating Phases

- We assume phases in the (universal) gaugino mass parameters.
- This choice leads to signatures in electric dipole moments similar to those ones present in the MSSM, and hence suppressed by the large values of the CP-odd Higgs mass.
- Choosing the phase in the Higgs sector, however, may lead to a realistic scenario. It is an open question if this can be tested.

Huber, Konstantin, Prokopec, Schmidt’06

The diffusion equations for the evaluation of the baryon density takes into account the interaction rates and sources

Huet and Nelson'93

$$v_\omega n'_Q = D_q n''_Q - \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$-6\Gamma_{ss}\left[2\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\frac{n_Q + n_T}{k_B}\right] + \tilde{\gamma}_Q$$

$$v_\omega n'_T = D_q n''_T + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] + \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$+3\Gamma_{ss}\left[2\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\frac{n_Q + n_T}{k_B}\right] - \tilde{\gamma}_Q$$

$$v_\omega n'_H = D_h n''_H + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_h \frac{n_H}{k_H} + \tilde{\gamma}_{\tilde{H}_+}$$
$$v_\omega n'_h = D_h n''_h + \rho\,\Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h/\rho}{k_H}\right] - (\Gamma_h + 4\,\Gamma_\mu)\,\frac{n_h}{k_H} + \tilde{\gamma}_{\tilde{H}_-}$$

No Baryon number violation:
Chiral charges generated from CP-violating sources (gamma's)

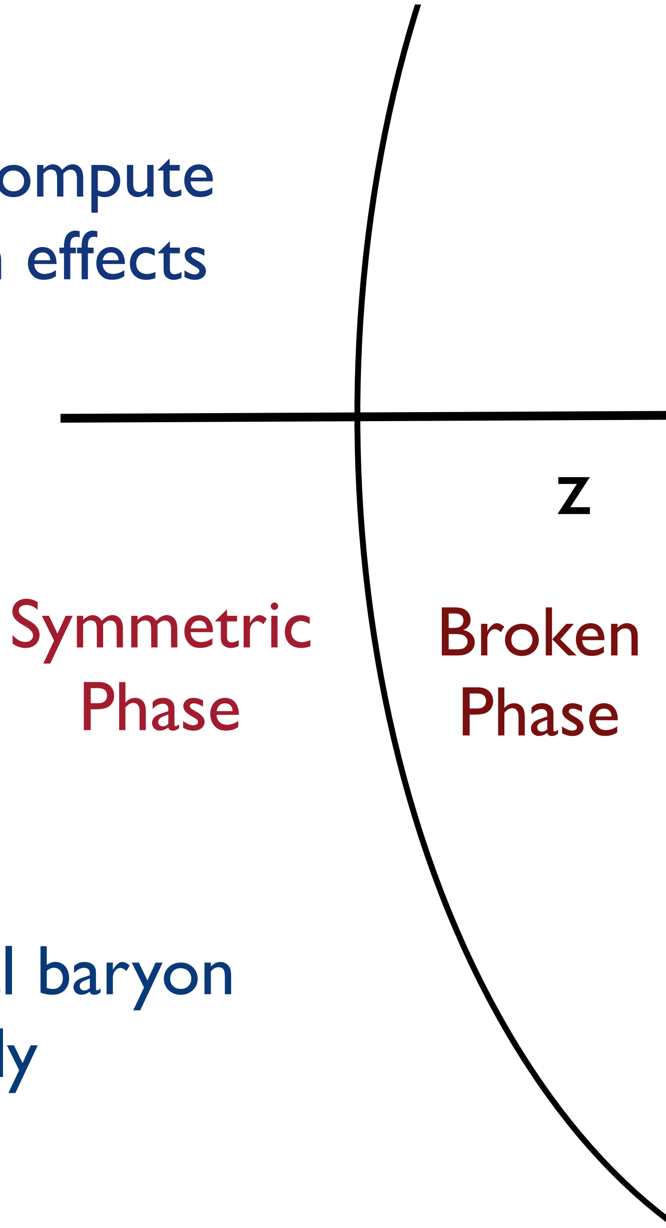
Here the ki's are statistical factors relating the densities to chemical potentials and the Gammas are rates per unit volume. In particular,

$$\Gamma_{ws} = 6\,\kappa_{ws}\,\alpha_w^5 T, \quad \Gamma_{ss} = 6\,\kappa_{ss}\,\frac{8}{3}\,\alpha_s^4 T$$

$$\Gamma_X = \frac{6\,\gamma_X}{T^3}$$

Once the chiral charge is obtained, we can compute the baryon number generation via sphaleron effects

$$v_\omega n'_B(z) = -\theta(-z)\left[n_F \Gamma_{ws} n_L(z) + \mathcal{R} n_B(z)\right]$$



Here R is the relaxation coefficient

$$\mathcal{R} = \frac{5}{4} n_F \, \Gamma_{ws}$$

The solution to this equation gives the final baryon number density in the broken phase, namely

$$n_B = -\frac{n_F \Gamma_{ws}}{v_\omega} \int_{-\infty}^{0} dz \, n_L(z) \; e^{z\mathcal{R}/v_\omega}$$

Computation of sources

The sources can be computed from the corresponding currents in the varying Higgs background. They take the form

Riotto’95, Carena, Quiros, Riotto, C.W.’97, Kainulainen et al’01,Cline et al’01,
Carena, Moreno, Quiros, Seco, C.W. ’01--02

$$
\begin{aligned}
\tilde{\gamma}_Q &\simeq -\, v_\omega\, h_t^2\, \Gamma_{\tilde{t}}\, \mathrm{Im}(A_t \mu_c)\; H^2(z)\, \beta'(z)\; \{\mathcal{F}_B(z) + \mathcal{G}_B(z)\} \\
\tilde{\gamma}_{\widetilde{H}_+} &\simeq -\; 2\, v_\omega\, g^2\, \Gamma_{\widetilde{\mathcal{H}}}\, \mathrm{Im}(M_2 \mu_c)\, \Big\{ H^2(z)\, \beta'(z)\; [\mathcal{F}_F(z) + \mathcal{G}_F(z)] \\
&\quad +\; g^2\, H^2(z) \cos 2\beta(z) \left[H(z) H'(z) \sin 2\beta(z) + H^2(z) \cos 2\beta(z) \beta'(z) \right] \mathcal{H}_F(z) \Big\} \\
\tilde{\gamma}_{\widetilde{H}_-} &\simeq 2\, v_\omega\, g^2\, \Gamma_{\widetilde{\mathcal{H}}}\, \mathrm{Im}(M_2 \mu_c) \left[H(z) H'(z) \sin 2\beta(z) + H^2(z) \cos 2\beta(z) \beta'(z) \right] \\
&\qquad \Big\{ \mathcal{K}_F(z) + 2 \left(\Delta + \bar{\Delta} \right) \mathcal{H}_F(z) \Big\} \;\; .
\end{aligned}
$$

Observe the dependence on the CP violating parameters in the gaugino and stop sectors. Relevant bino contribution also exists

The dependence on the Higgs background reveals a dependence on the variation of the parameter beta, which vanishes at large values of the CP-odd mass, plus contribution that survives at large values of the non-standard masses

New CP Violating Phases

- One natural consequence of these phases are Electric Dipole Moments.
- Electric dipole moments violate P and CP symmetries.
- The intrinsic electric dipole moment d for elementary particles is defined with respect to its reaction to an electric field (spin 1/2) :

$$H = -\mu\left(\frac{2}{\hbar}\vec{S}\right)\vec{B} - d\left(\frac{2}{\hbar}\vec{S}\right)\vec{E} \qquad \mu\frac{2}{\hbar} = \frac{q}{2m}g$$

	$d\vec{S}$	$\mu\vec{S}$	$\vec{E}$	$\vec{B}$	$d\vec{S}\vec{E}$	$\mu\vec{S}\vec{B}$
P	+1	+1	-1	+1	-1	+1
T	-1	-1	+1	-1	-1	+1
C	-1	-1	-1	-1	+1	+1
CPT	+1	+1	+1	+1	+1	+1

- d is zero in QED. They are induced by weak interactions

Experimental Bounds

- No electric dipole moment of the electron or the neutron has been observed.

- Determination of d relies on clever ways of measuring the variation of the precession frequency in the presence of electric fields

$$\omega = \frac{2}{\hbar}\left(\mu B \pm dE\right)$$

- Hence,

$$d = \frac{\hbar \Delta\omega}{4E}$$

- Current Bounds

$$d_e < 1.1 \times 10^{-29} \text{ e cm}$$

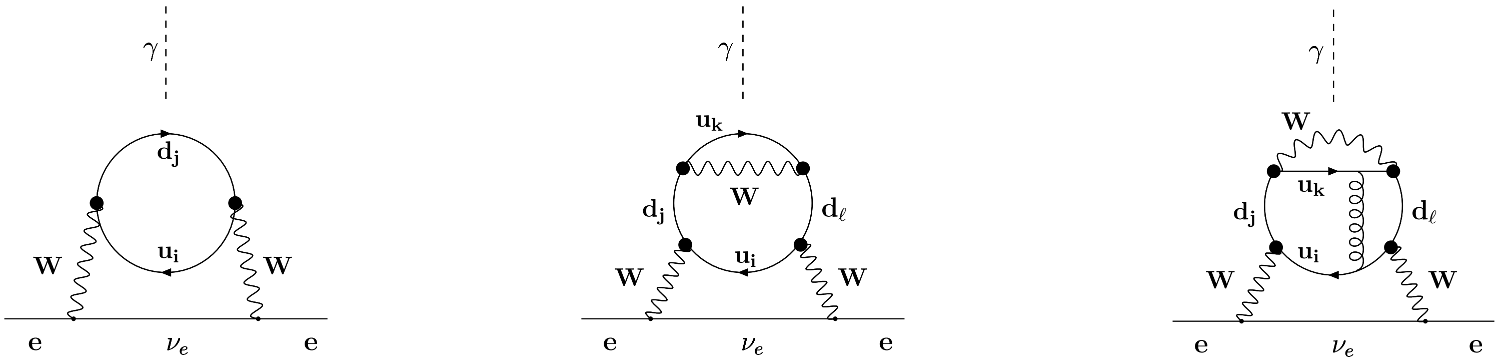
Uses polar molecules, like Thorium Monoxide, to increase electric fields

DeMille, Doyle, Gabrielse'18

Electric Dipole Moments

- What is remarkable is that the SM one, two and three loop contributions cancel,

Pospelov, Khriplovich ‘91



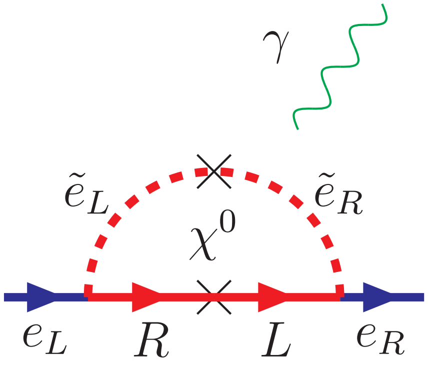
- And the first non-trivial contribution appears at four loops, and are proportional to the quark Jarlskog invariant

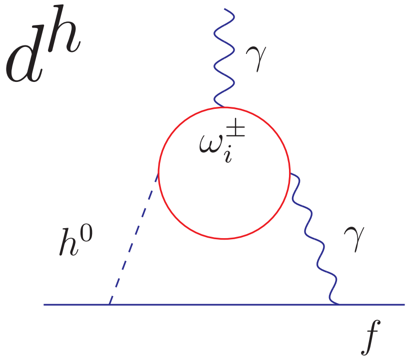
$$d_e^{(\mathrm{SM})}[\mathrm{one-gluon}] \sim \frac{\alpha_S}{4\pi} \cdot \frac{e G_{\mathrm{F}} m_e J \alpha^2}{256\pi^4} \simeq 3 \times 10^{-37}\ \mathrm{e\ cm} \qquad (m_{\nu_i} = 0\ \mathrm{assumed})$$

- This is much lower than the current limits. Another SM triumph.

New Physics for Baryogengesis

- The list of possible new physics contributions is very large. Nice review by Pospelov'05.
- There are one and two loop contributions that may cancel, but predictions typically close to experiments bounds.





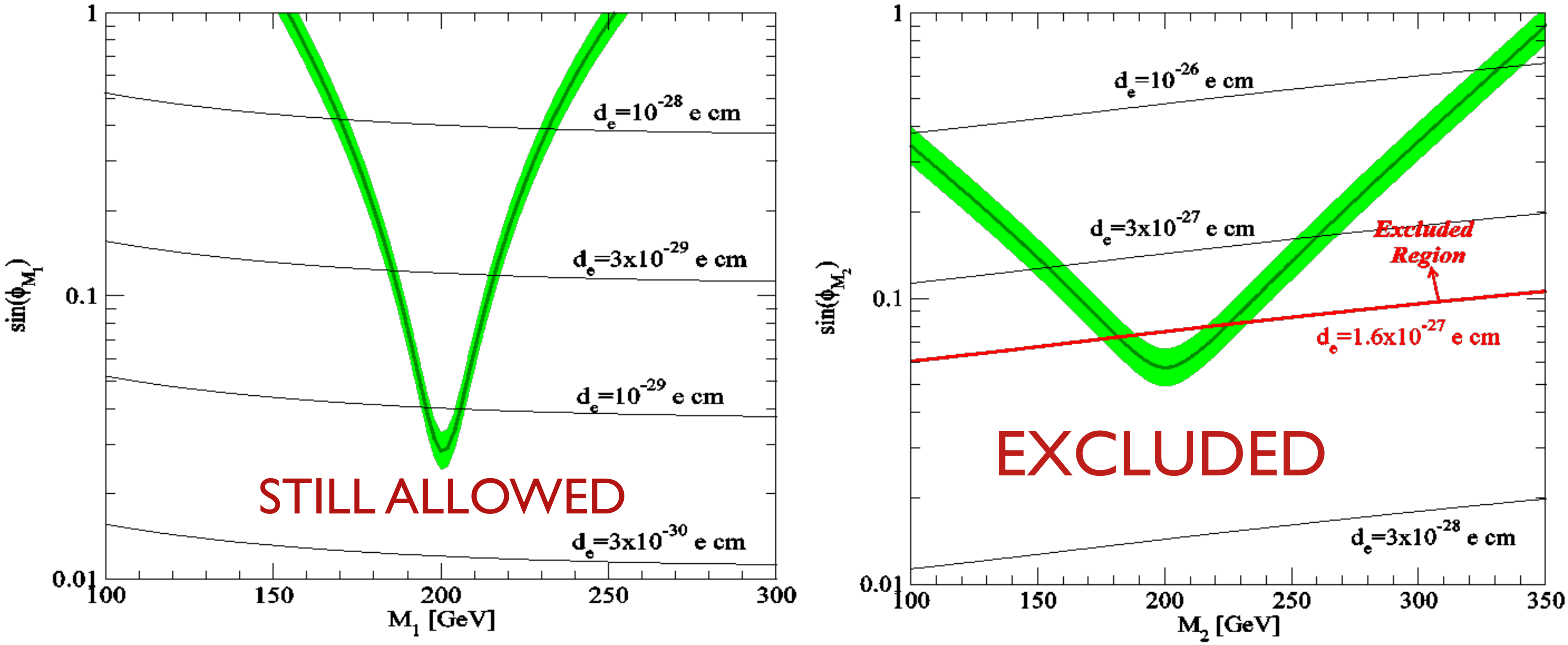
Chang, Keung, Pilaftsis'98-00, Ibrahim, Nath'00

- I encountered this problem by working on Baryogengesis scenarios and CP violation in the Higgs sector, and also last year, while trying to explain the galactic center excess from Dark Matter annihilation via the Higgs

M. Carena, J. Osborne, N. Shah, C.W.'19

Comparing bino- and wino-driven EWB

- Electron EDM: Heavy Scalars, no cancellations



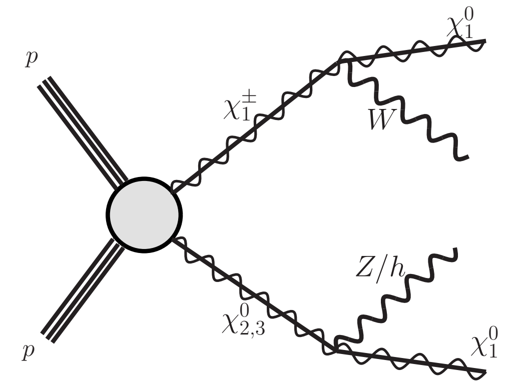
Sources have resonant behavior for μ equal to gaugino masses

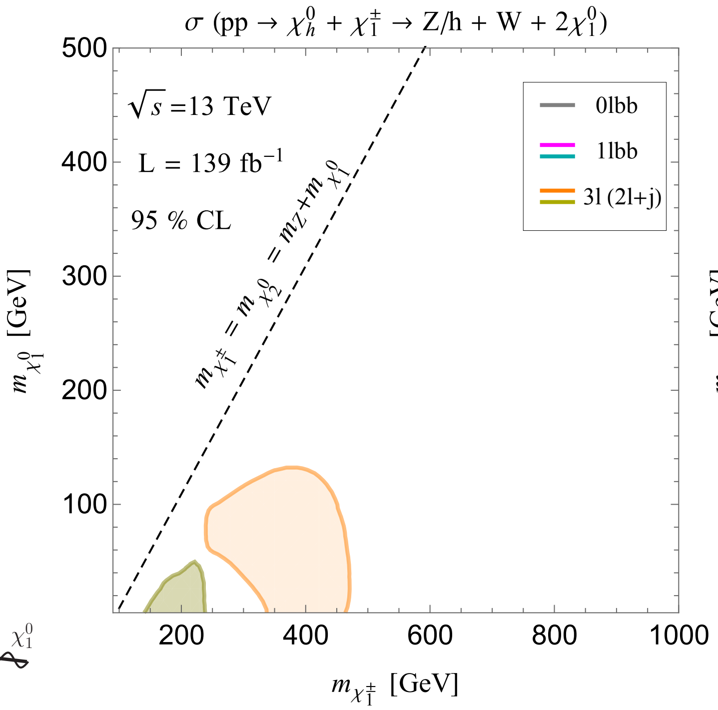
Cirigliano, Profumo, Ramsey-Musolf'06

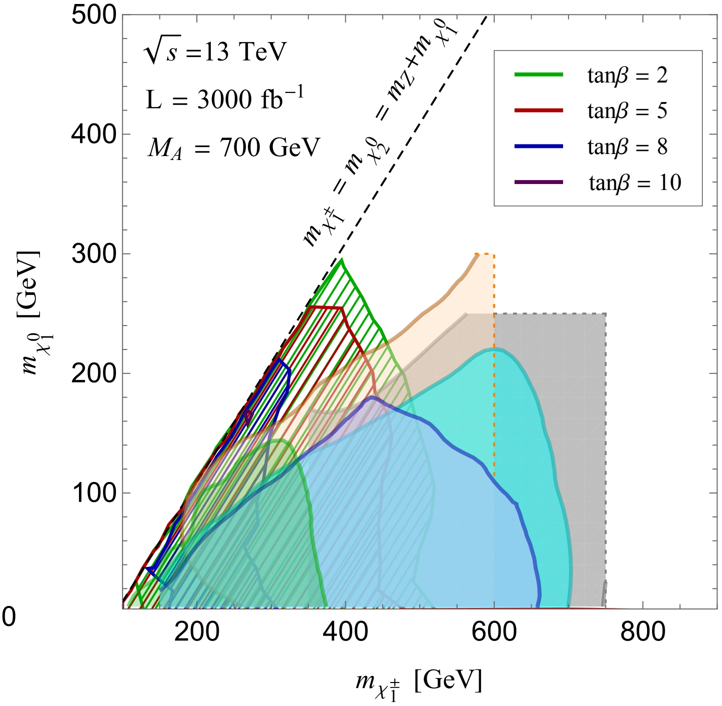
YL, S. Profumo, M. Ramsey-Musolf, arXiv:0811.1987

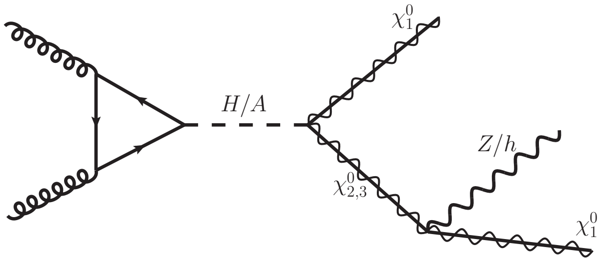
Collider Searches of Dark Matter sector at the LHC : Combination of Different Channels in Higgsino-Bino Scenario

Allows to probe potential
DM particle in a large range of masses







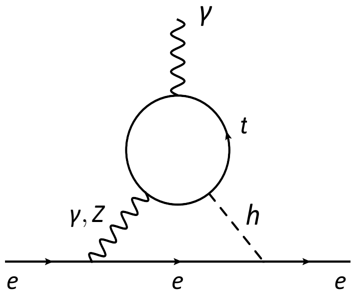


Jia Liu, Navin McGinnis, Xiaoping Wang, C.W. , 2006.07389

Creating Observed Asymmetry demands New CPV sources

Severe Challange: how to allow for required amount of CPV without upsetting Electric Dipole moments experimental bounds

Electron EDM and ACME II



Weak scale CPV $d_e \sim \frac{e\, G_F\, m_e}{(16\pi^2)^2}\, \vartheta_{\rm CPV} \sim 10^{-26}\, \vartheta_{\rm CPV}\, e\,{\rm cm}$

Latest electron EDM measurement ACME 2018

$$d_e < 1.1 \times 10^{-29}\, e\,{\rm cm}$$

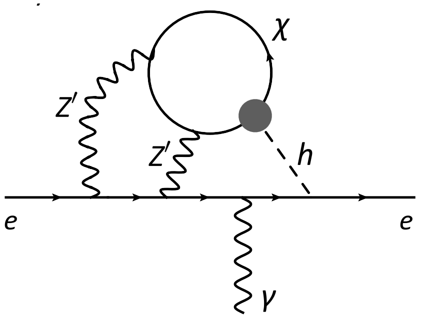
Most New Physics models of EWBG require $\sin\theta_{CPV} \geq 10^{-2}$

Dark CPV: a New mechanism for EW Baryogenesis

- **Higgs portal** (sourcing CP violation & phase transition)
- **Z’ port**al (for transfer of CP violation)

Z and EW Restoration

Z and EW NON- R



➔ leading EDM arises at higher loops

Carena, Zhang, Quiros’19

Electroweak Baryogengesis

Demands a strongly first order phase transition and CP violation, establishing a link between cosmology and physics at the weak scale

Transition via thermal effects induced by colored scalars strongly constrained

Additional Higgs bosons may lead to a strongly first order phase transition

Relevant constraints : Higgs precision measurements and searches for new Higgs bosons at the LHC.

Modification of Higgs trilinear couplings is an interesting signature, but will probably demand going beyond the LHC and should be part of a global fit.

It is very relevant to study the nucleation patterns, and not just the critical temperature. Relevant differences may be present.

CP-violating sources remain as the least explored chapter and tend to be in tension with electric dipole moment bounds.