Unified picture of electroweak symmetry breaking and family structure

Junji Hisano (Nagoya Univ.)
On behalf of research group B02

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"Physics in LHC and early universe"
Date:9th to 11th, January, 2017
Place: The University of Tokyo

Contents of this talk

- **Introduction of B02**
- **Precision studies of the Higgs coupling**

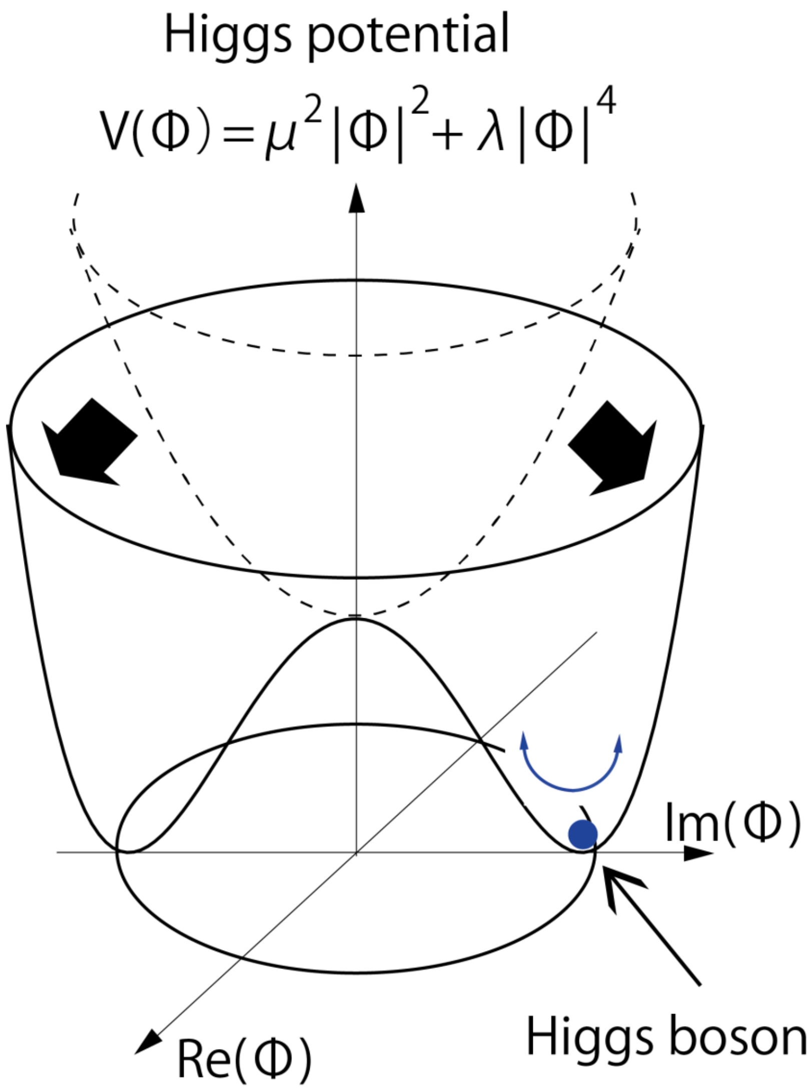
  Electroweak Phase Transition, Elecroweak baryogensis
- **Higgs mass in SUSY SM**
- **Tools of analysis for searches for NP @ LHC**

NEW ERA COMES !

Higgs sector is a window to the BSM.

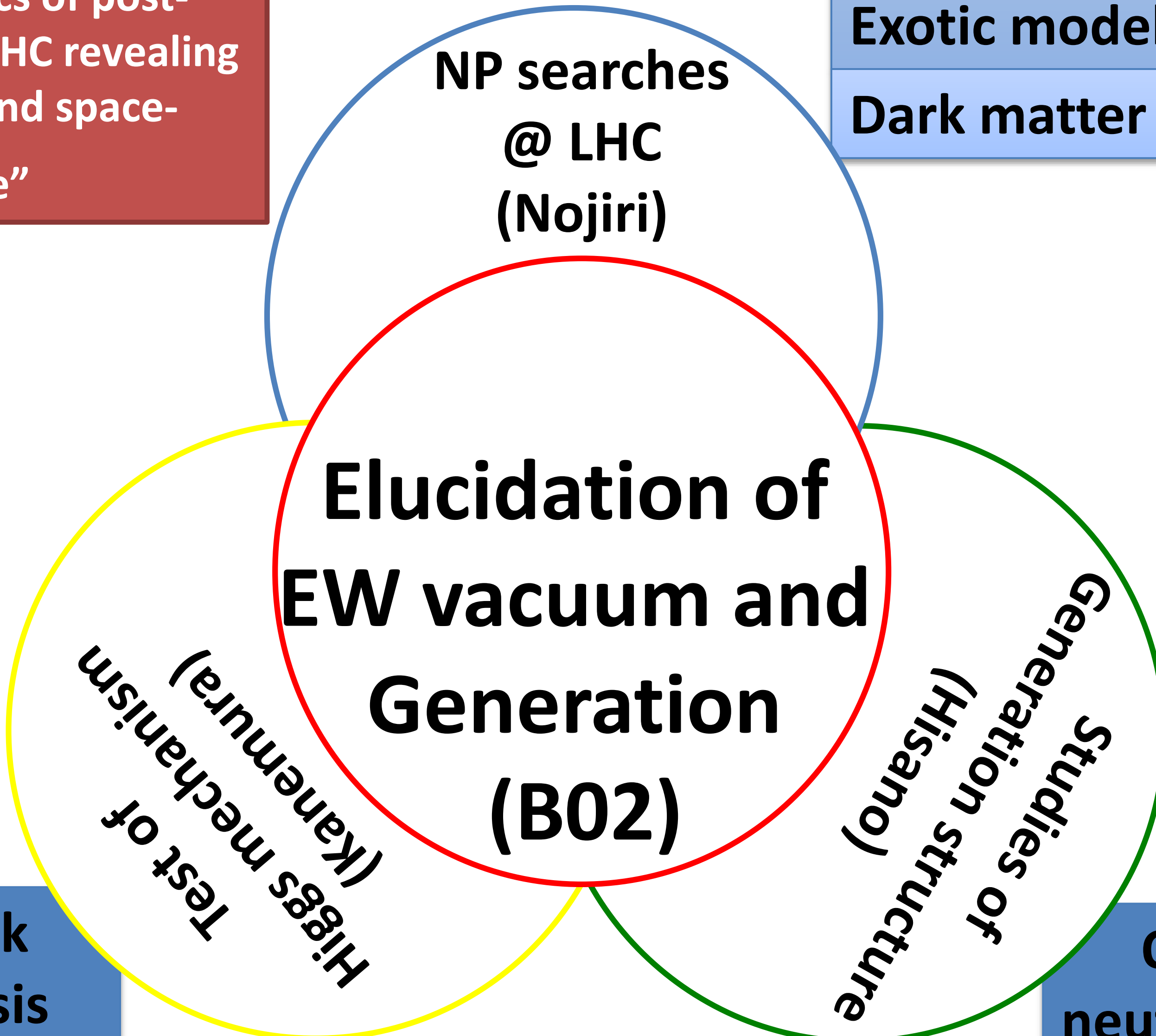
- What derives μ^2 to be negative ?
- What stablizes the radiative correction to μ^2 ?
- Higgs doublet is only one or more?
- Higgs fields are only SU(2) doublet?

These questions are linked to the BSM@TeVs.



Innovative Areas
“New expansion of particle physics of post-Higgs era by LHC revealing the vacuum and space-time structure”

- Supersymmetric models
- Exotic models
- Dark matter models



Electroweak baryogenesis

Origin of neutrino masses

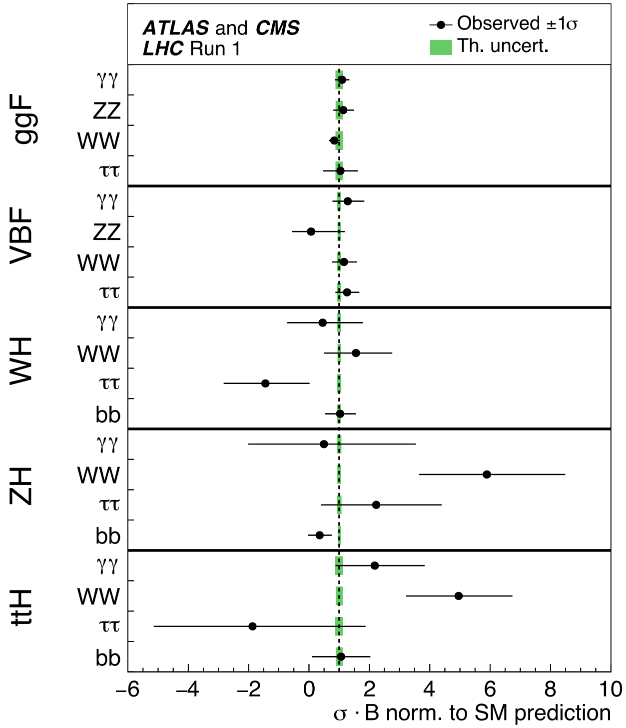
Many collaborators and associate researchers

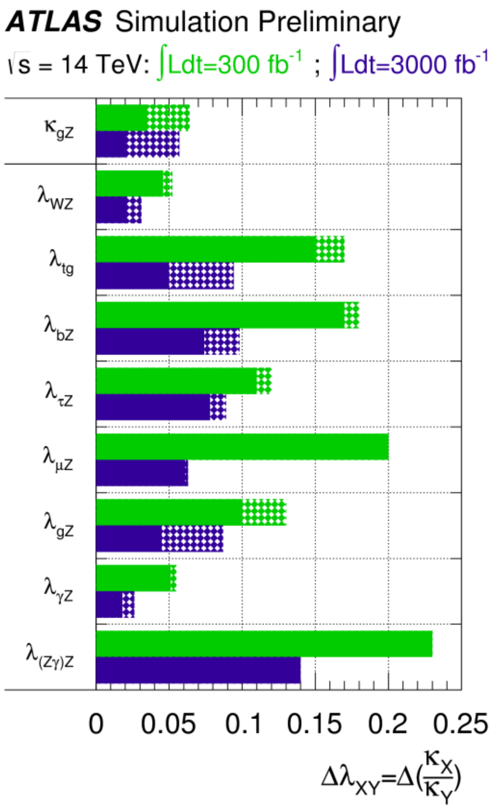
Precision studies of the Higgs coupling

Precision studies of the Higgs coupling is coming

Higgs couplings will be measured at LHC with precision

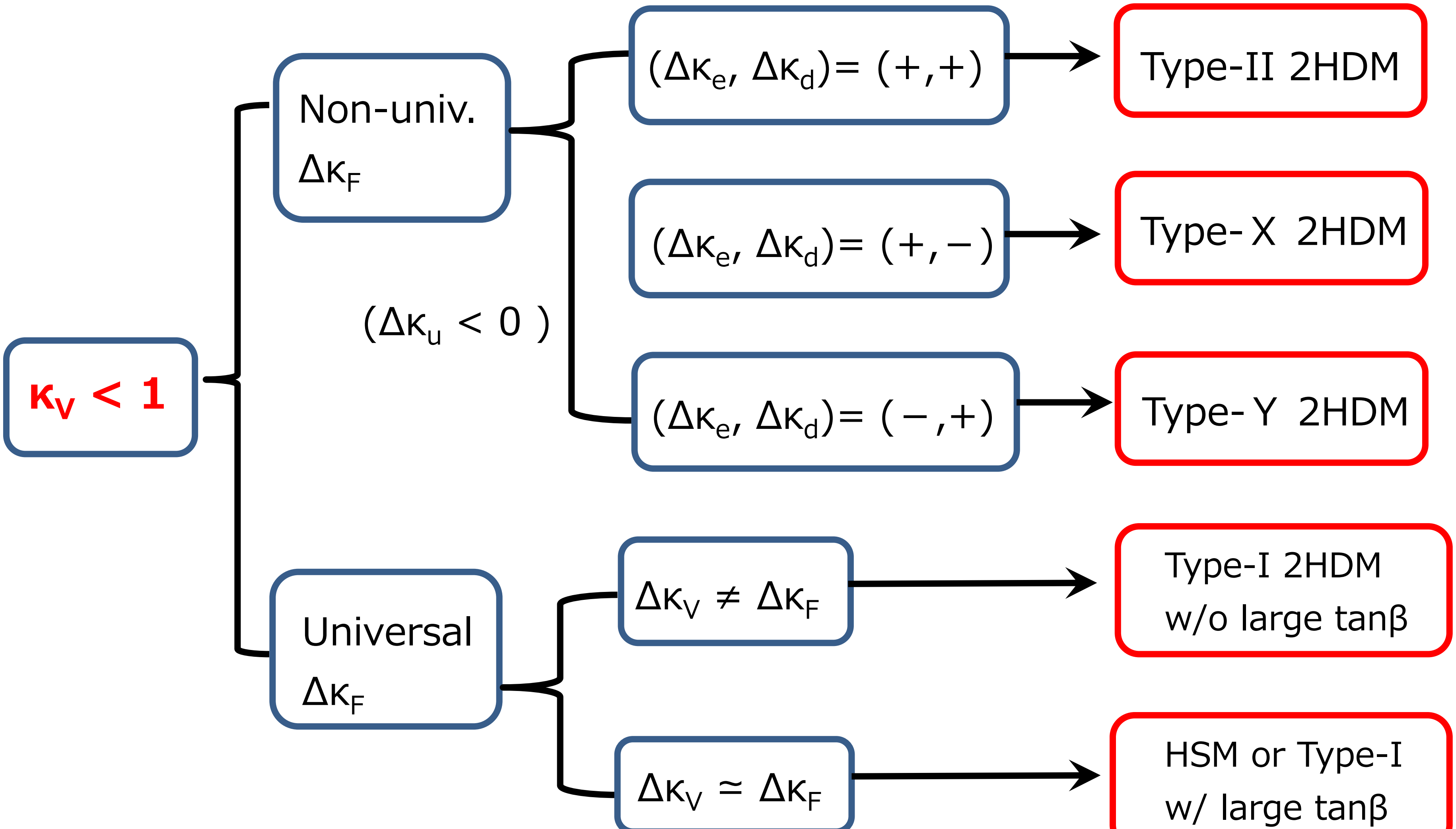
- **3-5% for W, Z and gamma**
- **~7 % for muon**
- **5-10 % for t, b, and tau.**





arXiv:1606.02266

Once $\kappa_V \neq 1$ is detected we can separate models



If $\kappa_V > 1$, exotics (triplet, septet, …)

Predictions on the Higgs couplings in various Higgs models

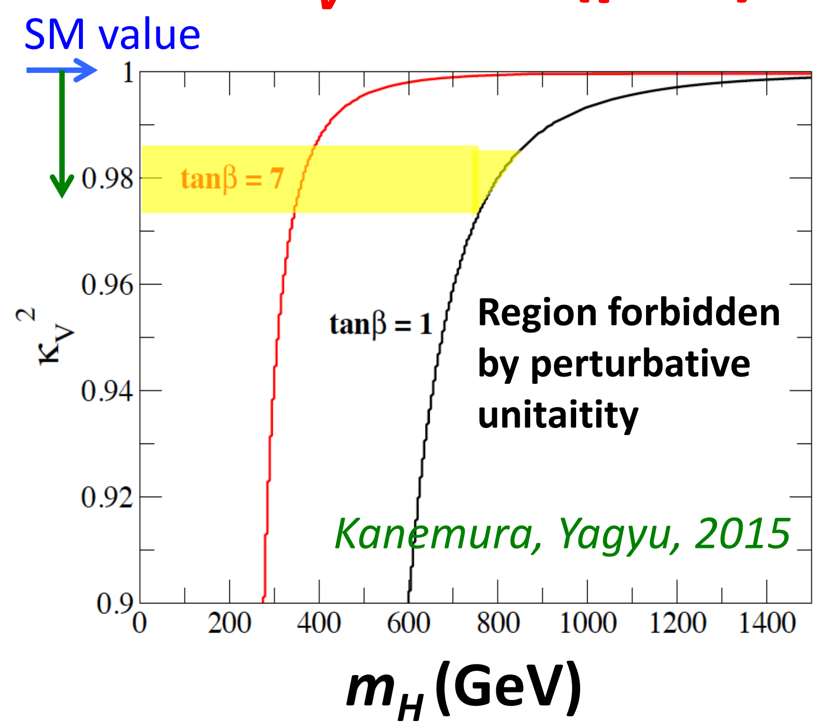
The deviation in Higgs couplings
= Upper bound on the mass of the second Higgs

Prediction on Higgs couplings in various Higgs models
→ Fingerprinting models by precision tests

Precision calculation of Higgs couplings with one-loop corrections in various extended Higgs sectors
H-COUP Projects (Kanemura et al)

Scale factor for the Higgs coupling with weak bosons

$$\kappa_V^2 = \sin^2(\beta-\alpha)$$



H-COUP Project

Kanemura, Kikuchi, Yagyu, Sakurai

A full set of *Fortran Code* for evaluating one-loop corrected *h*(125) couplings in various extended Higgs models

Renormalization in the *modified* on-shell scheme

★ The gauge dependence in the *h* couplings from C.T. of mixing angles is removed.

Doublet-Singlet model

SK, Kikuchi, Yagyu, NPB907 (2016) , arXiv:1608.01582

2HDMs (I, II, X, Y)

SK, Kikuchi, Yagyu, PLB731, 27 (2014) , NPB896, 80 (2015)

SK, Okada, Senaha, Yuan, PRD70 (2004)

Doublet-Triplet model

Aoki, SK, Kikuchi, Yagyu, PLB714 (2012) , PRD87 (2013)

Inert Doublet/Singlet model

SK, Kikuchi, Sakurai, arXiv:1605.01582

h(125)-couplings

hgg, hγγ, hγZ, hZZ, hWW, htt, hbb, hττ, Hhh, *and S, T, U, …*

H-COUP (ver.1) is released in the near future

Example of the results by H-COUP

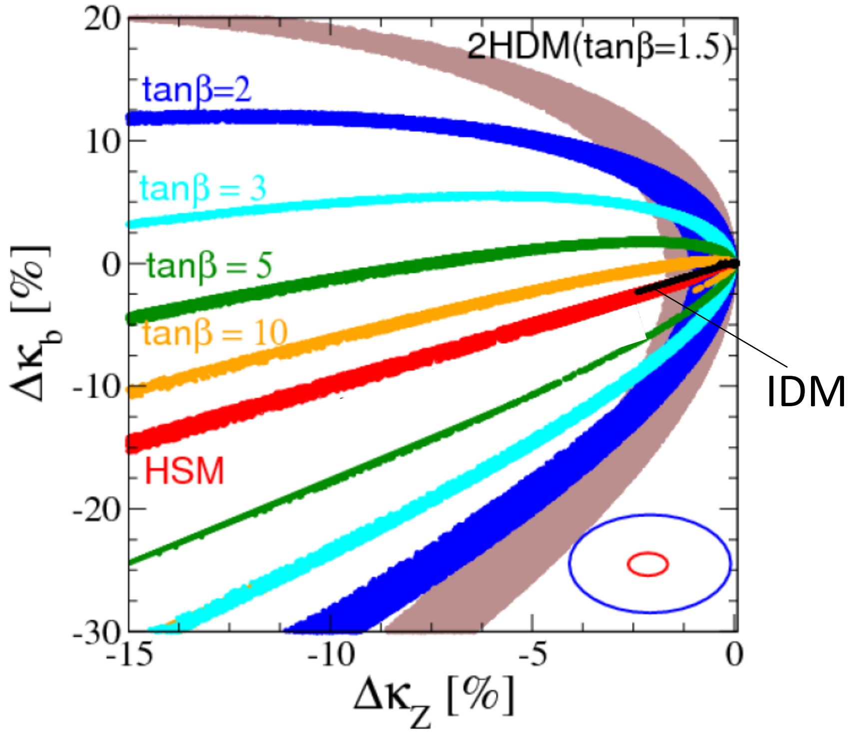
Comparison of
1. 2HDM-I
2. Doublet-Singlet Model (HSM)
3. Inert Doublet Model (IDM)

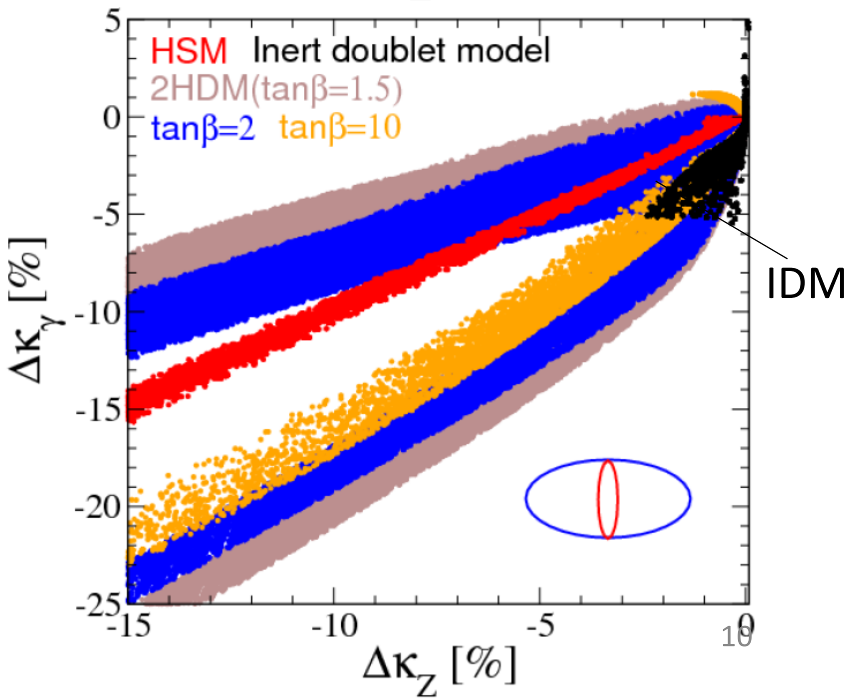
Scan of inner parameters (mass, mixing angles) under the theoretical conditions of
Perturbative unitarity
Vacuum stability
Condition for avoiding wrong vacuum (HSM)

These models may be distinguished, as long as a deviation in κ_Z is detected

Ellipse, ±1σ at LHC3000 and ILC500

Kanemura, Kikuhci, Yagyu, 2015





Electroweak Phase Transition, LHC and Gravitational Waves

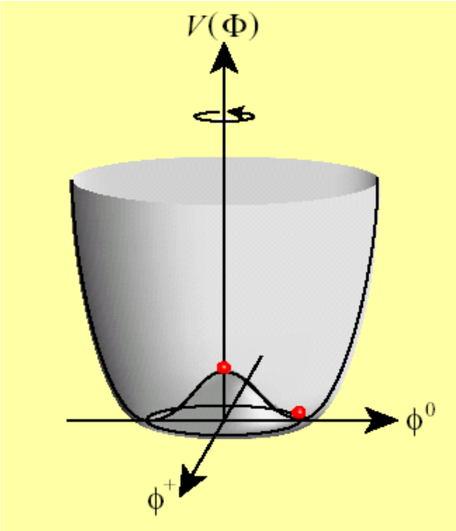
Higgs potential is the last unknown part in the SM

Dynamics of EWSB

EW phase transition (1st or 2nd)

1st OPT is required for successful EW baryogenesis

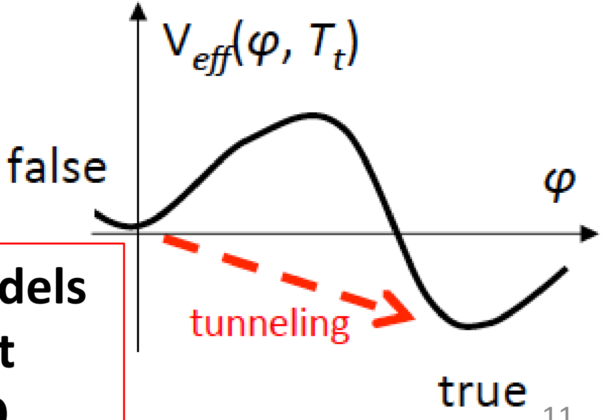
which affects the Higgs couplings and causes Gravitational Waves



Can we test the scenario of 1st OPT
by using LHC and future gravitation waves?

Higgs coupling κ will be measured more precisely at (HL-) LHC

LISA has been approved and the experiment will start in 2028. (before ILC)

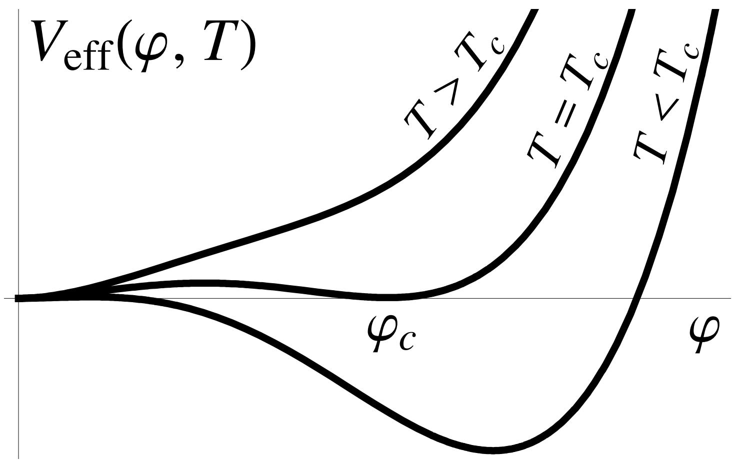


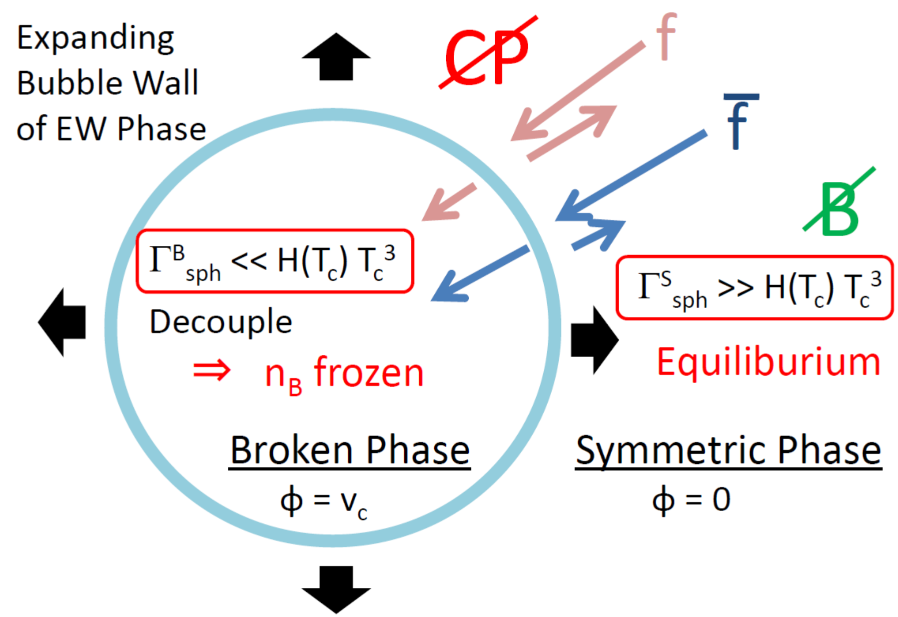
We may be able to test the 1st OPT in a class of models by the synergy of Higgs couplings measurements at the LHC and the GW measurement at LISA/DECIGO

Strongly 1st OPT (EW Baryogenesis)

$\Gamma \sim e^{-E_{\rm sph}/T} \ (T < T_c)$
$\Gamma \sim \kappa(\alpha_W T)^4 \ (T_c < T)$

Sakharov conditions:
- B Violation → **Sphaleron transition at high T**
- C and CP Violation → **New CP Phases**
- Departure from Equilibrium → **1st Order EW Phase Transition**





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

(Sphaleron Rate) < (Expansion Rate) ⇒ $\boldsymbol{\varphi_c/T_c > 1}$

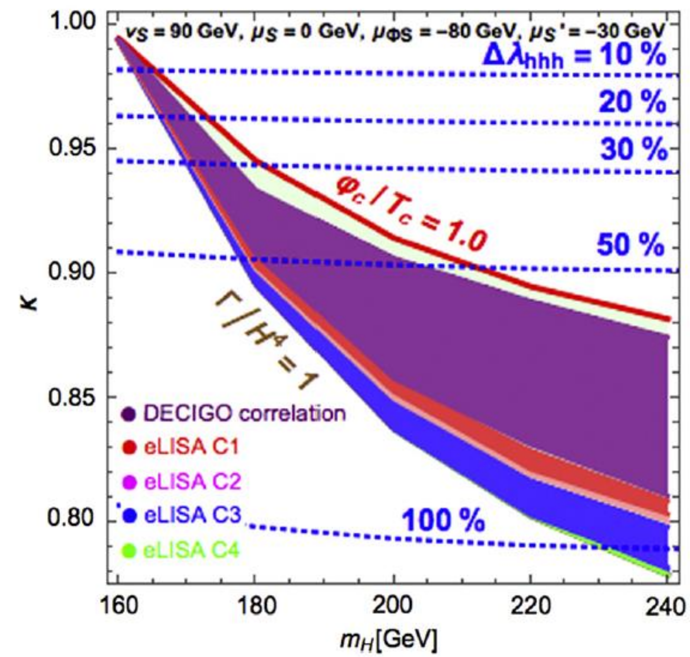
Higgs singlet model

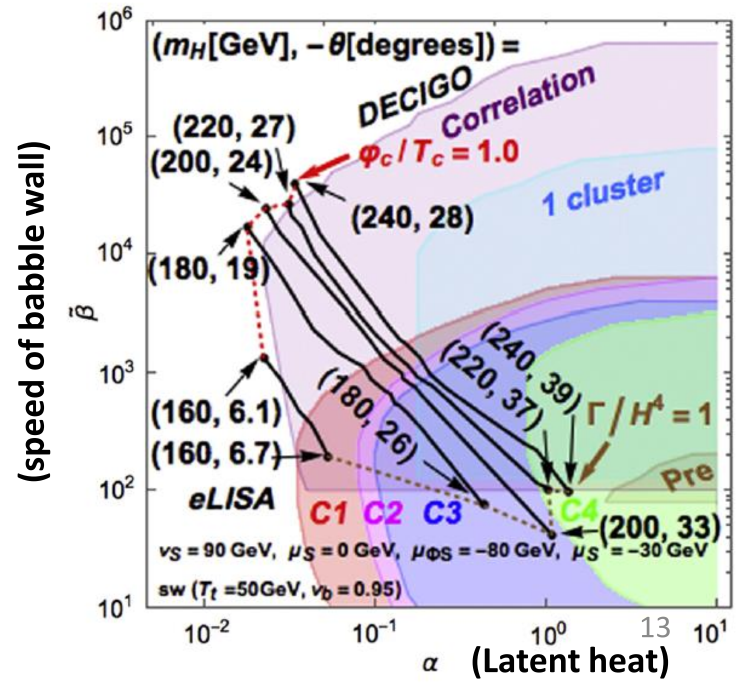
The mixing between doublet and singlet scalars causes deviation in *κ* and *hhh* couplings, and also cause GWs if 1st OPT

Measuring *hVV* and *hff* couplings at LHC (and the self-coupling *hhh* at HL-LHC), a class of models for electroweak Baryogenesis of 1st OPT can be tested

In the future, by a combined study with the measurement of the GW spectrum at LISA, such models for electroweak baryogenesis may be well identified

Hashino, Kakizaki, Kanemura, Ko, Matsui, 2016



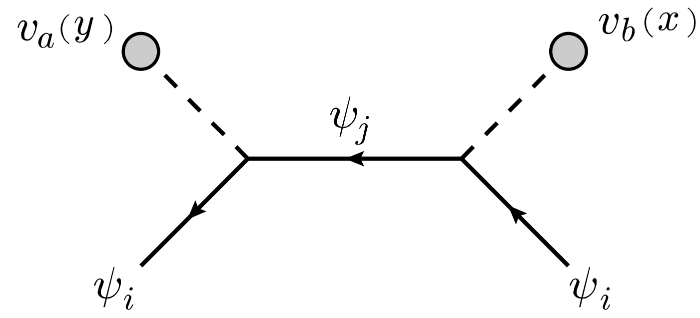


EW baryogenesis and EDMs

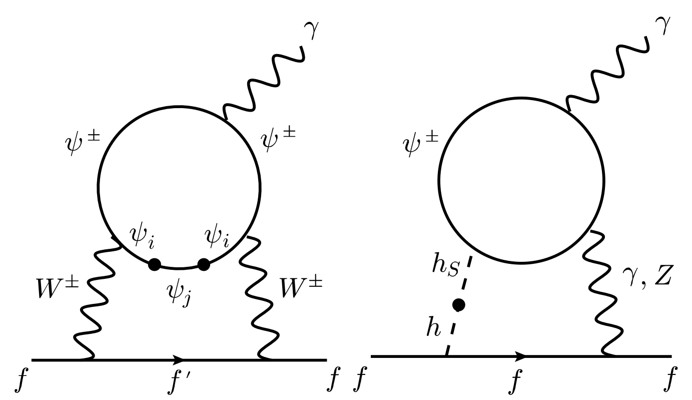
Electroweak baryogenesis needs new CP violation, which induces EDMs of electron, neutrons and atoms.

Introduction of non-colored extra fermions with CP violating coupling with Higgs fields. (ex., doublet (ψ) and signlet fermions ($\tilde{S}$))

Electroweak baryogeneis is high-temperature phenomena, and we need to evaluate baryon number in the original theory (not effective one including High-D op.) in order to correctly incorporate the resonant enhancement in thermal bath.



Interaction of extra fermion with BG Higgs fields

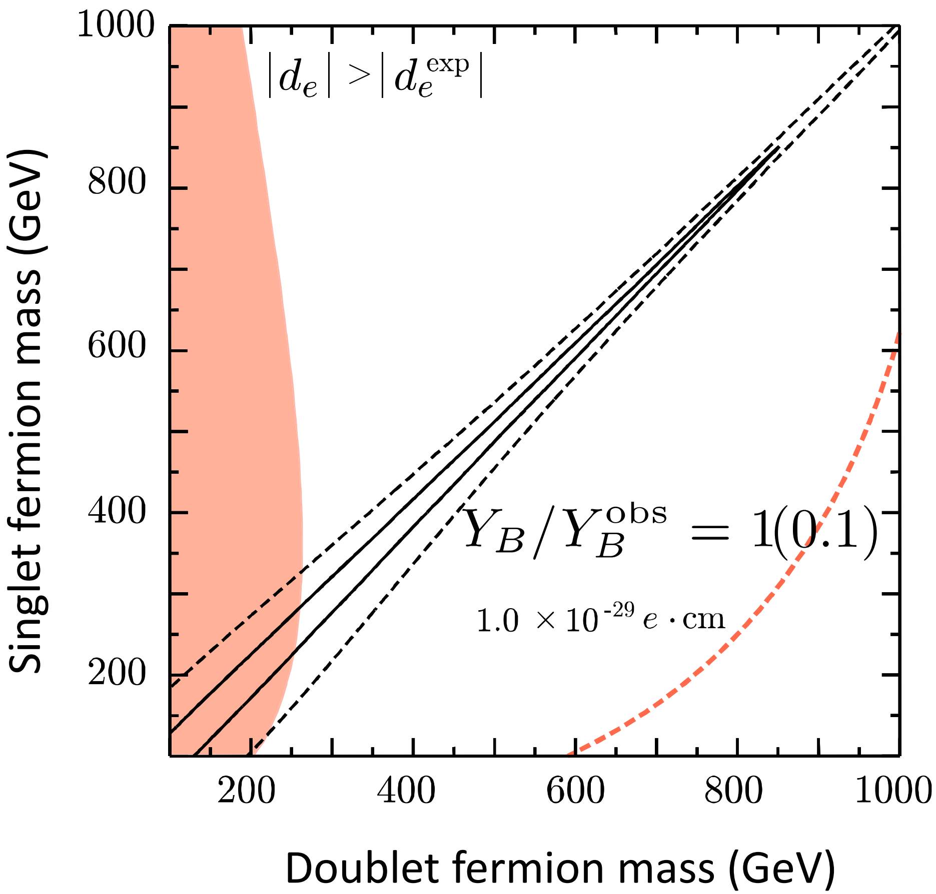


Barr-Zee diagrams for EDMs

EW baryogenesis and EDMs

Electron EDM bound from ACME experiment (2013):
$|d_e| < 8.7 \times 10^{-29}$ e cm (ThO)

Neutron and proton EDMs are around ~10^{-28} e cm. Their measurements are complimentary to electron one since accidental cancelation may suppress them.



Fuyuto, JH, Senaha, 2015

Higgs mass in SUSY SM

SUSY SM gives a chance to understand questions,

- **what derives μ^2 to be negative ?**
- **what stablizes the radiative correction to μ^2 ?**

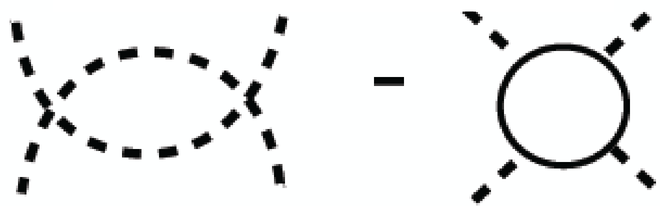
125 GeV Higgs mass in the MSSM

Tree level

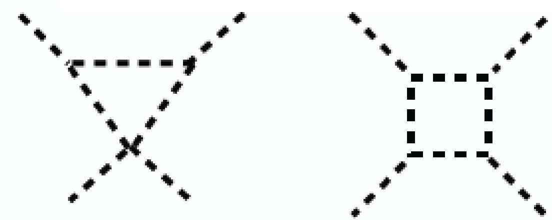
One-loop correction

$$m_{h^0}^2 \lesssim m_Z^2 \cos^2\beta + \frac{3}{4\pi} y_t^2 m_t^2 \sin^2\beta \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{X_t^4}{m_{\tilde{t}}^4} \right)$$

Large log correction



Finite correction



$$X_t = A_t - \mu/\tan\beta$$

- **Large stop mass (** $m_{\tilde{t}} \gg m_Z$**)**
- **Large A_t term (** $X_t/m_{\tilde{t}} = \pm\sqrt{6}$**)**
- **New interaction (New Yukawa, U(1)’, NMSSM, …)**

Effects on Higgs mass from extra matters

Assumption:

Soft scalar masses for squarks and sleptons in SUSY SM, including A terms, are zero @ GUT scale (gaugino mediation).

0. If extra matter have Yukawa coupling with Higgs, additional radiative correction to m_h appears. **(Moroi and Okada)**

1. If N_5=3,4 (N_5: number of pair of SU(5) 5 and 5^*), large A_t is radiatively derived since $SU(3)_C$ is asymmetric non-free. ***(Moroi, Yanagida, Yokozaki, 2013/16)***

2. If extra scalars have soft mass much larger than gaugino masses, large A_t is effectively derived since stop masses are radiatvely reduced. ***(JH, Kuwahara, &Kuramoto, 2016)***

Large A_t due to N_5=3,4

Parameters	Point **I**	Point **II**	Point **III**	Point **IV**	Point **V**
N_5	3	3	4	4	3
M_3 (GeV)	3000	3540	6900	6300	3400
M_1/M_3	1	1.0	0.83	1	0.7
M_2/M_3	1	0.61	0.62	1	1
m_0 (GeV)	0	0	0	4000	0
$m_{H_{u,d}}/1$ TeV	3.441	0	0	6.392	0
$\tan\beta$	10	25	6	5	32.9
μ (GeV)	229	3410	5270	194	3210
A_t (GeV)	-4030	-4450	-7050	-6720	-4480
Particles	Mass (GeV)	Mass (GeV)	Mass (GeV)	Mass (GeV)	Mass (GeV)
$\tilde{g}$	2470	2970	1890	1760	2840
$\tilde{q}$	3670–3890	4340–4400	5360–5370	5900–6070	4150–4410
$\tilde{t}_{2,1}$	3220, 2130	3780, 3250	4390, 3130	4760, 2560	3720, 2940
$\tilde{\chi}^{\pm}_{2,1}$	942, 232	3410, 669	5240, 537	884, 196	3210, 1110
$\tilde{\chi}^0_4$	942	3410	5240	884	3210
$\tilde{\chi}^0_3$	537	3410	5240	590	3210
$\tilde{\chi}^0_2$	238	669	537	203	1110
$\tilde{\chi}^0_1$	227	645	510	191	420
$\tilde{e}_{L,R}(\tilde{\mu}_{L,R})$	1510, 911	1140, 1080	1630, 1420	4580, 4260	1700, 715
$\tilde{\tau}_{2,1}$	1500, 860	1150, 983	1630, 1420	4580, 4250	1650, 423
$H^{\pm}$	3730	3290	5590	6910	3040
$h_{\text{SM-like}}$	125.2	125.2	126.3	125.6	125.2

(Moroi, Yanagida, Yokozaki 2016)

Gluino can be lighter than ~3TeV. LSP depend on models.

Large A_t due to large soft mass (N_5=1)

Models	1	2	3	4
$m_{D'}$ [TeV]	15	30	25	30
$m_{L'}$ [TeV]	15	0	0	0
$M_{1/2}$ [TeV]	1.80	1.96	1.80	1.92
M_1/M_3	1	1	1	3
$m_{h_{1/2}}$ [TeV]	0	0	2	0
m_h [GeV]	125.2	125.0	125.9	125.4
$m_{\tilde{t}_{1,2}}$ [GeV]	2153, 2609	789, 1783	820, 1839	1088, 1612
$m_{\tilde{b}_{1,2}}$ [GeV]	2585, 2763	1740, 1770	1814, 1979	1539, 1733
$m_{\tilde{\tau}_{1,2}}$ [GeV]	464, 886	425, 1196	417, 1093	1506, 1956
$m_{\tilde{u}_{L,R}}$ [GeV]	2884, 2790	2105, 1795	2248, 2016	1994, 2091
$m_{\tilde{d}_{L,R}}$ [GeV]	2884, 2784	2106, 1790	2249, 2010	1995, 1765
$m_{\tilde{e}_{L,R}}$ [GeV]	889, 481	1199, 446	1102, 460	1514, 1969
$m_{\tilde{g}}$ [GeV]	3082	3168	2954	3103
$m_{\tilde{\chi}_1^0}$ [GeV]	594	644	362	1196
$m_{\tilde{\chi}_2^0}$ [GeV]	1134	1221	375	1617
$m_{\tilde{\chi}_3^0}$ [GeV]	2121	1669	597	1619
$m_{\tilde{\chi}_4^0}$ [GeV]	2124	1676	1136	1956

(JH, Kuwahara, Kuramoto, 2016)

- **Stop can be around 1 TeV.**
- **Stau LSP is strongly constrained. R-parity breaking or axino LSP ?**
- **Wino or Higgsino LSP are possible , depending on the BCs.**

Tools of analysis for searches for NP @ LHC

- NLO calculation
- gluon-quark separation
- Photon jets
-

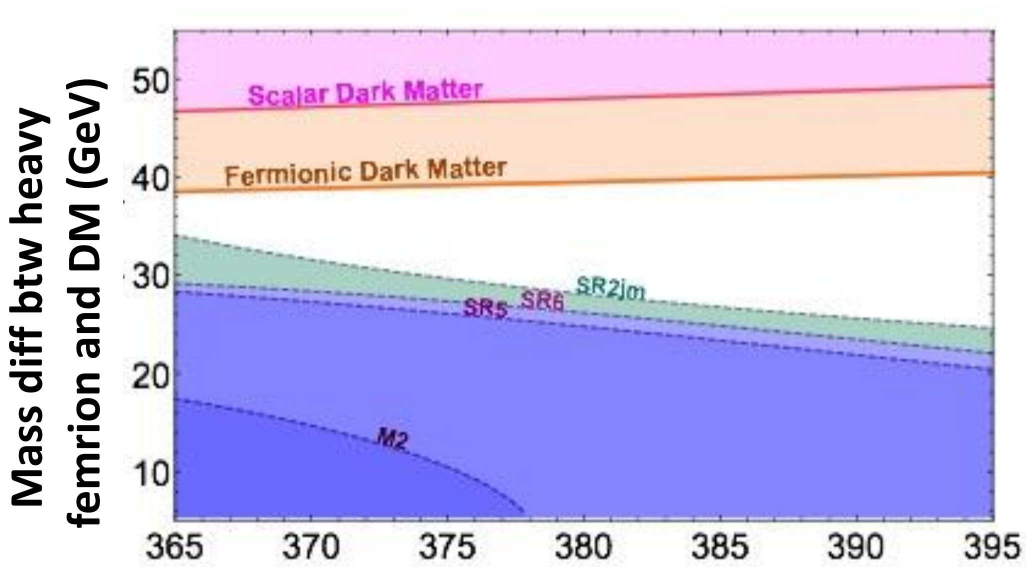
Anomalies are chances to develop methods for analysis.

Degenerate Heavy colored fermion coupled with DM

Heavy colored fermion was motivated from 750 GeV diphoton excess.

$$pp \to X\bar{X} \to S \to gg, \gamma\gamma, ZZ, \ldots$$

Degeneracy between heavy colored fermion and DM are favored from DM abundance due to coannihilation.



Systematic uncertainty is assumed 16%.

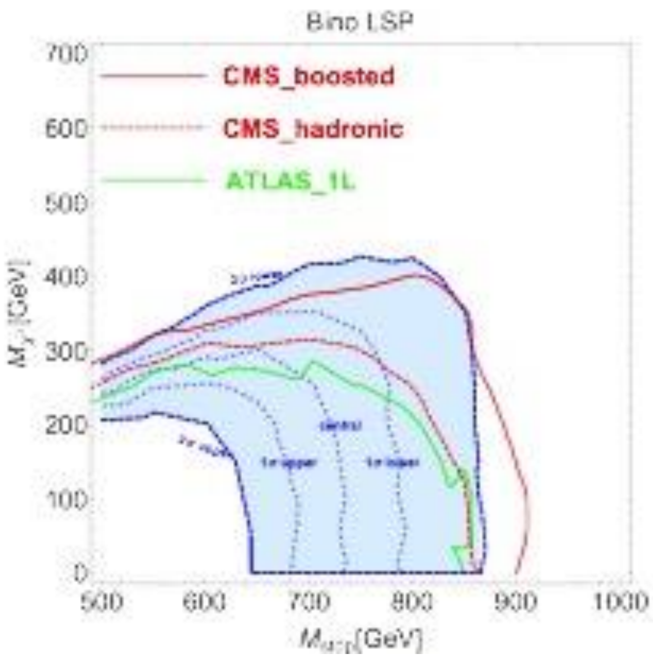
(Han, Ichikawa, Matsumoto, Nojiri, Takeuchi 2016)

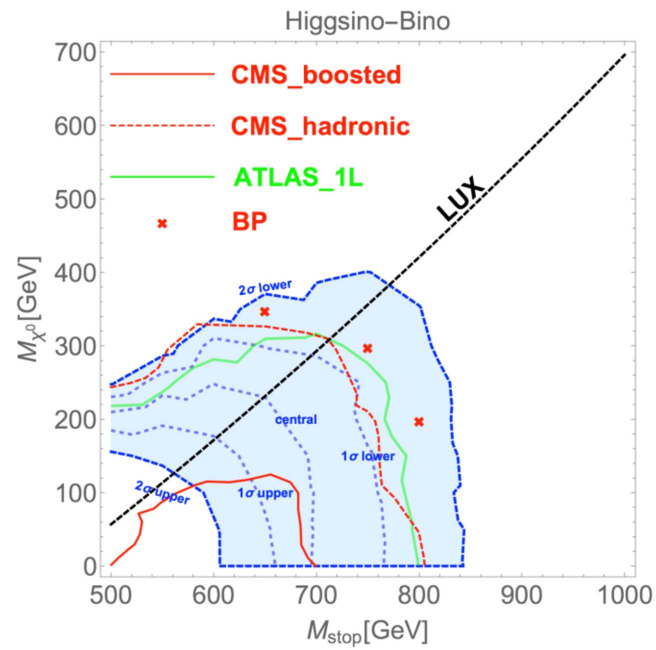
Limits are se … , are working on BSM NLO generators.

>2 σ excess in stop search with l+jets+E_T^{Miss} channel

Simplified model (stop→Bino) is almost excluded due to CMS boosted top search, while decay pattern stop→Higgsino→Bino+W(→l) is allowed.

(Han, Nojiri, Takeuchi, Yangida, 2016)





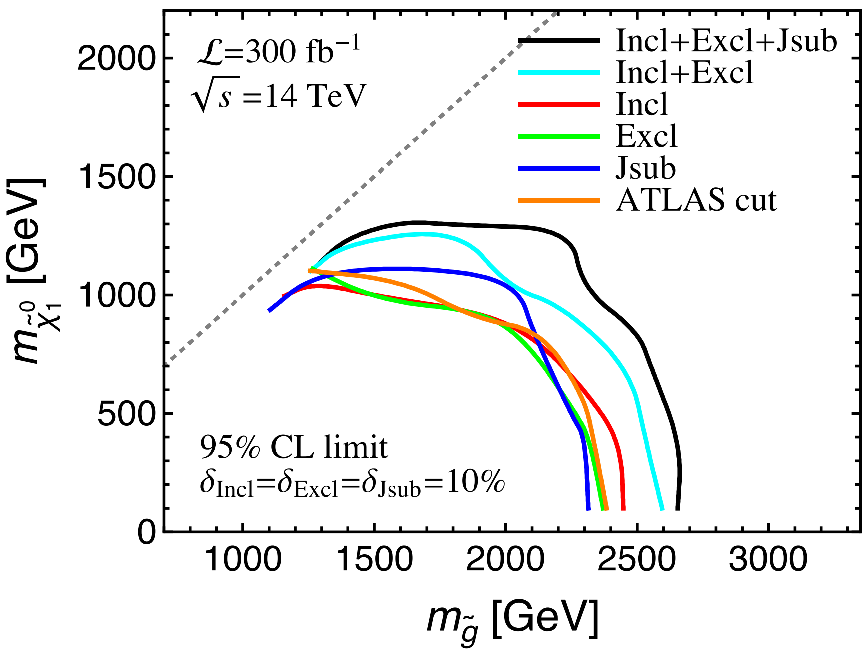
Simplified model may not capture the feature of the original model. How to express "signature" ?

Application of q-g discrimination: Search for gluino pair production

Quark and gluon initiated jets are different. In parton shower, quark split into hard q and soft g, and gluon split into two g's more equally.

Constraint from search $pp \to \tilde{g}\tilde{g} \to 4q + \text{missing}$

BG: Z+more gluons



Improvement of S/N leads to discovery up to kinematic endpoint.
The discrimination is important when systematics is dominant factor.

(Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 2016)

Summary

Elucidation of EW vacuum and Generation, which is target of B02, is now one of most important subjects. We need your contribution and supports on the researches.