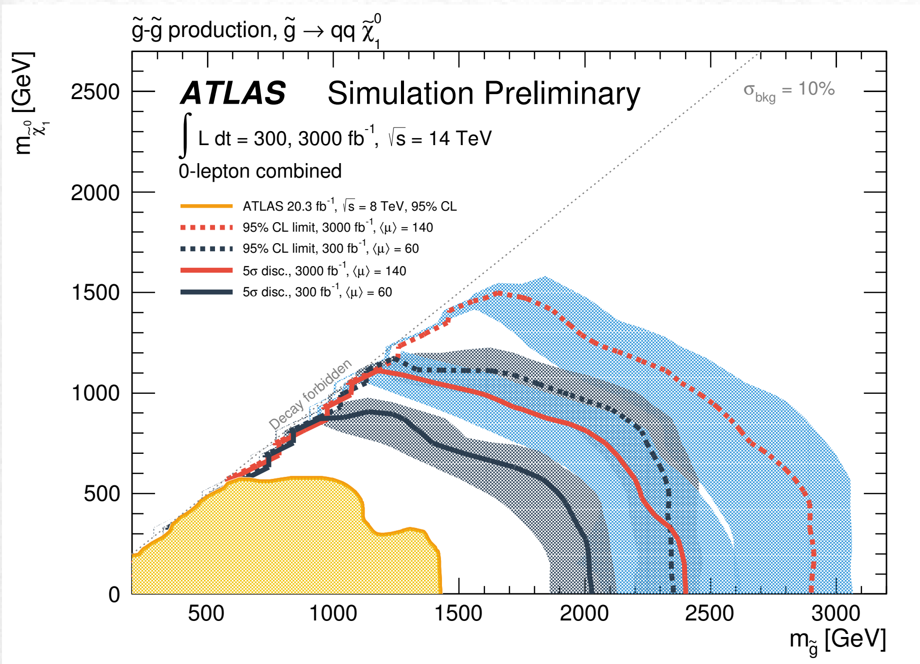
Footprint of BSM Higgs sector

Mihoko Nojiri (KEK &IPMU)
based on work with
Motoi Endo, Takeo Moroi
(Tokyo University)
and work with
Hirohisa Kubota(KEK)

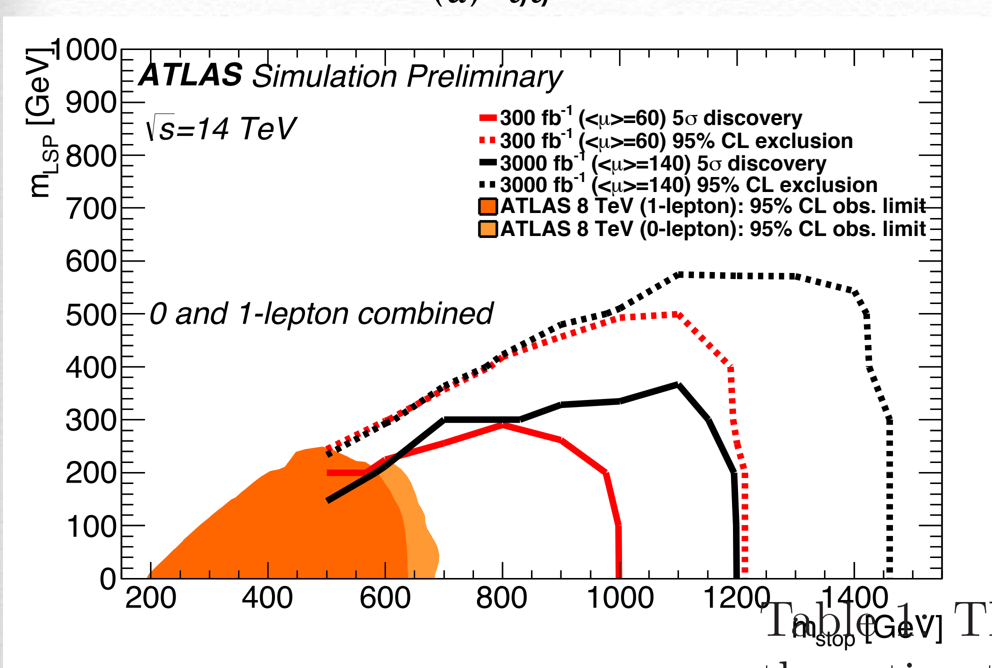
starting soon
LHC at 13TeV toward HL-LHC



(a) $\tilde{q}\tilde{q}$

Exclude gluino mass up to 3TeV and degenerate case LSP mass up to 1.5TeV

scalar top up to 1.4TeV



discovery potential of stop
—Future prospects 1309.1514

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 GeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
VLHC	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Table 1: The first line gives the current bound on stops from the LHC [7]. The rem the estimated 5σ discovery reach in stop pair production cross section and mass fo hadron collider runs.

: The 95% CL exclusion limits (dashed) and 5σ discovery reach (solid) for 300 fb^{-1} (red) and
(black) in the $\tilde{t}, \tilde{\chi}_1^0$ mass plane assuming $\tilde{t} \to t + \tilde{\chi}_1^0$ with a branching ratio of 100%. The

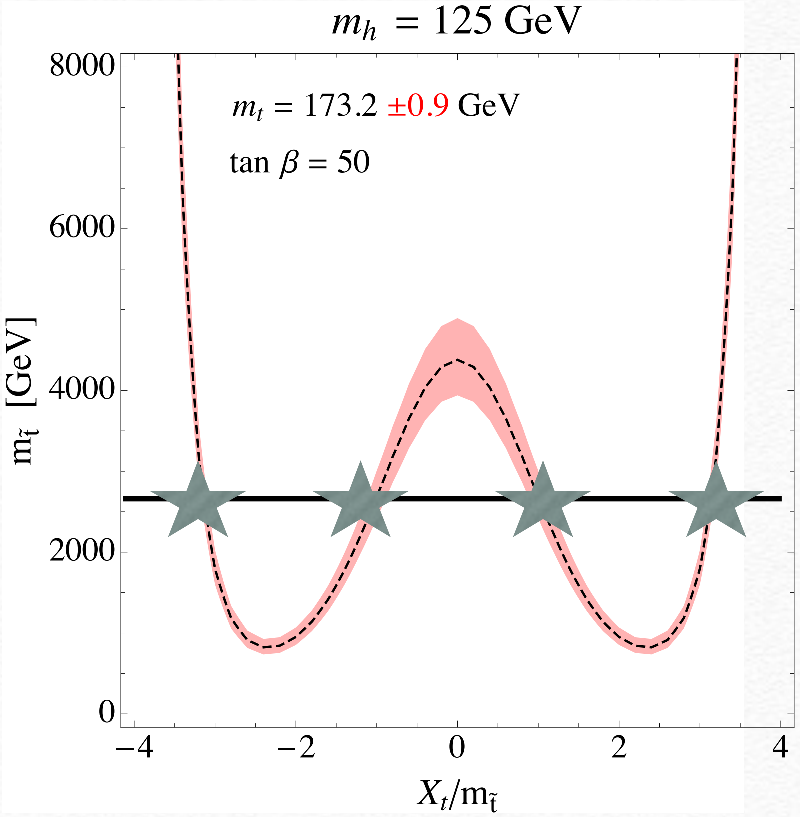
If we do not find "anything" at LHC, HL-LHC

- Should we build e+ e- collider?
- New channel: Higgs production and decay.
- How much we can learn by looking into Higgs sector in SUSY, MCHM,….
- New: CCB constraint and Higgs decays

SUSY Higgs sector

- Type II   model
- SUSY: 4point Higgs coupling~ gauge coupling
- Radiative correction from top sector Higgs mass ⇆ SUSY scale and stop mixing

Okada Yamaguchi Yanagida
Ellis Ridolfi Zwirner
Haber Hempfling (1991)



from Gilly Elor et al 1206.5301

$$\delta m_h^2 \simeq \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right],$$

$$X_t = A_t - \mu \cot\beta$$

up to 4 solutions for given stop mass

leading Higgs mass ~ one loop correction
Y_t^4, X_t^4 dependent Large correction
(NLO, yukawa and QCD correction)

Connection to Higgs Sector
Bottom Yukawa coupling in MSSM(At and μ)

- Non-holomorphic terms in the Yukawa coupling enhanced by tanβ, non-decoupling

- Large correction to the bottom Yukawa coupling if $\mu<0$ and A_t large, but suppressed by m_A^{-2} decoupling

effective Lagrangian

Hall Rattazzi Sarid (93)
Hempfling, Carena Olechowski Pokorski(94)

$$-\mathcal{L}_{\rm eff} = y_b\,\epsilon_{ij}\bar{b}_R H_d^i Q_L^j + \Delta y_b\,\bar{b}_R Q_L^k H_u^{k*} + y_t\,\epsilon_{ij}\bar{t}_R Q_L^i H_u^j + \Delta y_t\,\bar{t}_R Q_L^k H_d^{k*} + \text{h.c.},$$

effective Yukawa

Carena Mrenna Wagner

$$\begin{aligned} g_{h\bar{b}b} &= -\left(\frac{\sin\alpha}{\cos\beta}\right)\frac{1-\Delta_b\cot\alpha\cot\beta}{1+\Delta_b}\,g_{h\bar{b}b}^{(\rm SM)} \\ &= \left[\sin(\beta-\alpha) - \frac{\tan\beta-\Delta_b\cot\beta}{1+\Delta_b}\cos(\beta-\alpha)\right] g_{h\bar{b}b}^{(\rm SM)}, \end{aligned}$$

sign of Δb ~sign of μ makes difference

y_b(MSSM)

$$y_b(M_{\rm SUSY}) \simeq \frac{\sqrt{2}m_b(M_{\rm SUSY})}{v\cos\beta(1+\Delta_b)}.$$

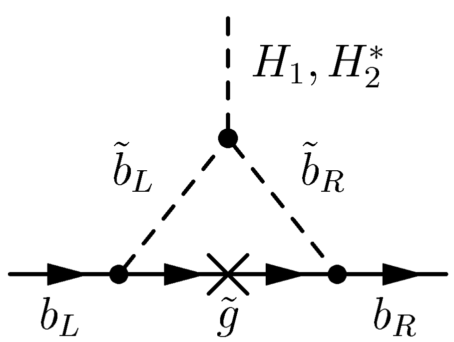
$$\Delta_b \simeq \left[\frac{2\alpha_s}{3\pi}M_3\mu\, I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, M_3^2) + \frac{y_t^2}{16\pi^2}\mu A_t\, I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)\right]\tan\beta,$$

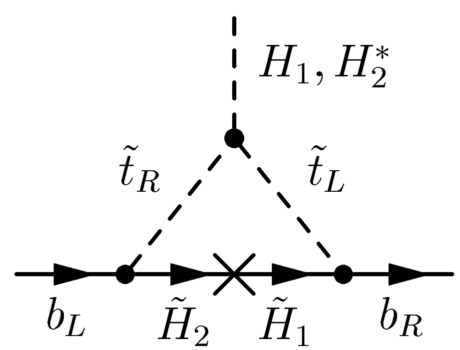
Higgs branch and b-> s transition

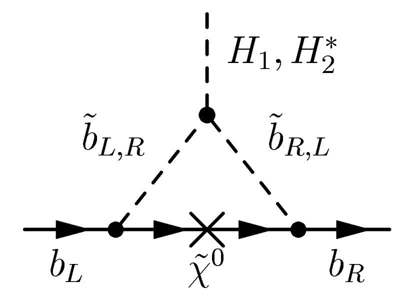
H→bb

non decoupling for fixed mA

$$\mathcal{L}^{1\,\text{loop}} = (y_b + \Delta y_{b,1})\bar{b}_R b_L H_1^0 + (\Delta y_{b,2})\bar{b}_R b_L H_2^{0*} + \text{h.c.}$$







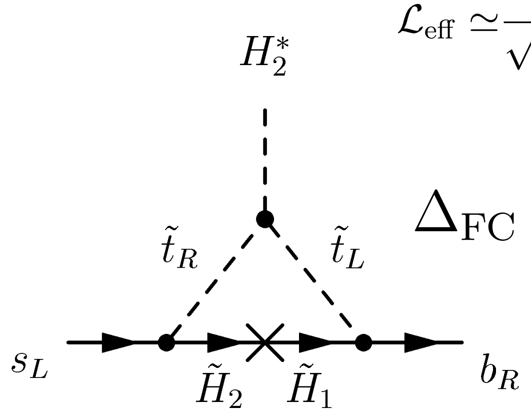
$$\mathcal{L} = \frac{\sqrt{2}m_i}{v_{SM}}\Phi_1^0 \bar{d}_R^i d_L^i + \lambda_2^{ij}\Phi_2^0 \bar{d}_R^i d_L^j + \text{h.c.}$$

Babu Kolda… using SuperISO 3.4 (Mahmoudi)

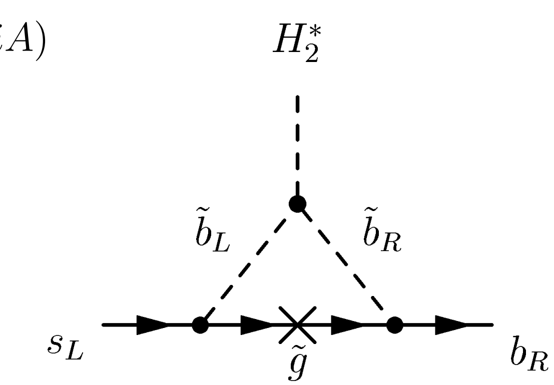
b→s transition

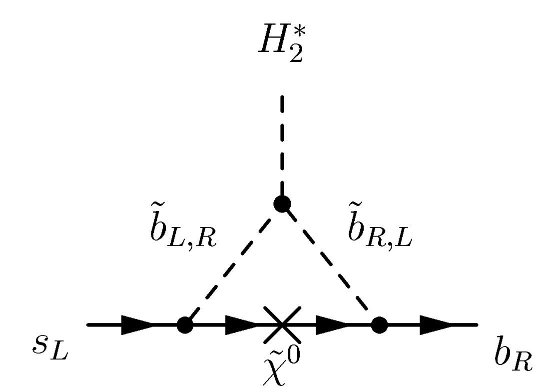
$$\mathcal{L}_{\text{eff}} \simeq \frac{g m_b}{\sqrt{2} m_W \cos\beta}\frac{\Delta_{\text{FC}}}{(1+\Delta_b)(1+\Delta_0)} V_{tb}V_{ts}^* \,(\bar{s}_L b_R)\,(H + iA)$$

$$\Delta_{\text{FC}} = \frac{y_t^2}{16\pi^2}\mu A_t \tan\beta\, I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2).$$



minimal





non minimimal

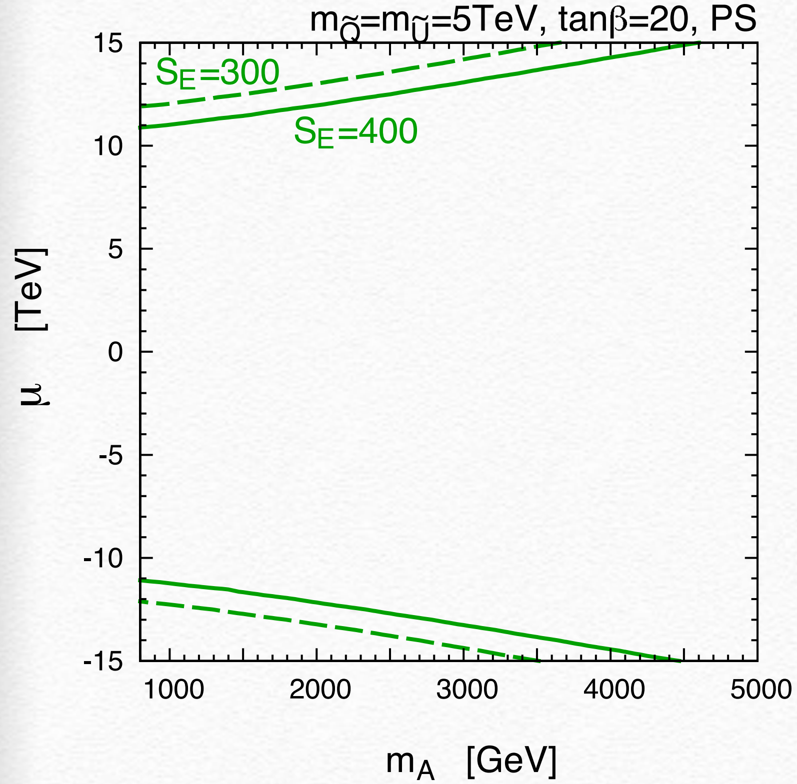
CCB vacuum

- Higgs-stop-sbottom potential can have minimum deeper than EW vacuum. (... Casas, Lleyda and Munoz '96)
- Sufficiently small transition rate needed (Coleman, Callan Coleman '77)
- Previously $A_t H_u t_L t_R$ term is considered but $\mu H_d t_L t_R$ term can be same order
  →upper bound to the mu parameter for given squark mass and mA.

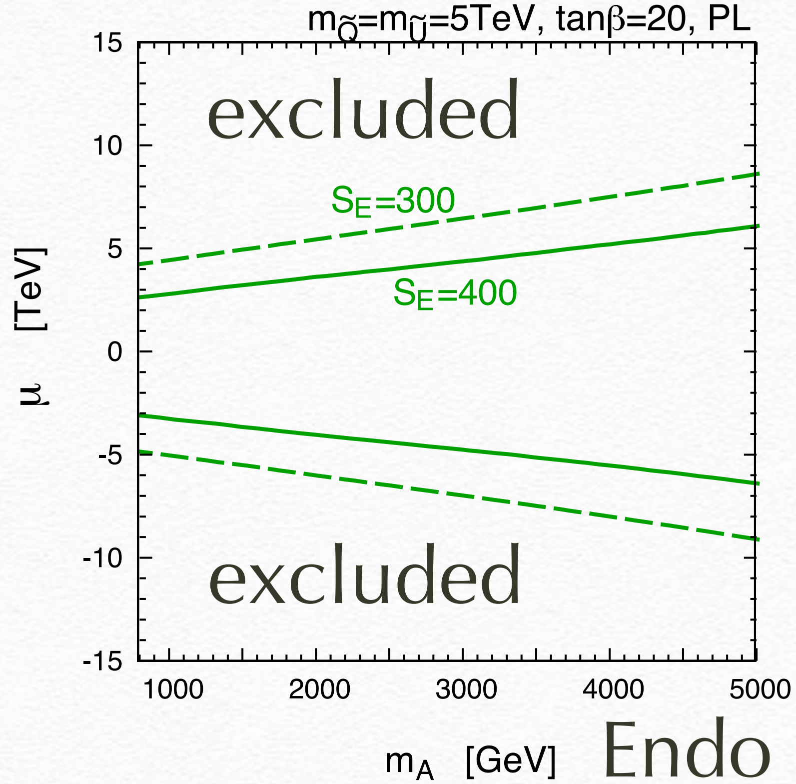
soft → ; ← susy

$$V = \frac{1}{2}m_{11}^2 h_d^2 + \frac{1}{2}m_{22}^2 h_u^2 - m_{12}^2 h_d h_u + \frac{1}{2}m_{\tilde{Q}}^2 \tilde{t}_L^2 + \frac{1}{2}m_{\tilde{U}}^2 \tilde{t}_R^2 + \frac{1}{\sqrt{2}}y_t(A_t h_u - \mu h_d)\tilde{t}_L\tilde{t}_R \quad \cdots\cdot$$

small A solution



Large A solution



contraint on μ!

numerical calculation
cosmoTransition 2.0a1

The CCB vacuum is studied in
Camrgo-Molina et 1309.7212
Chowdhury et al 1310.1932
Blinov et al 1310.4174
in different constraint.

Endo Moroi Nojiri to appear

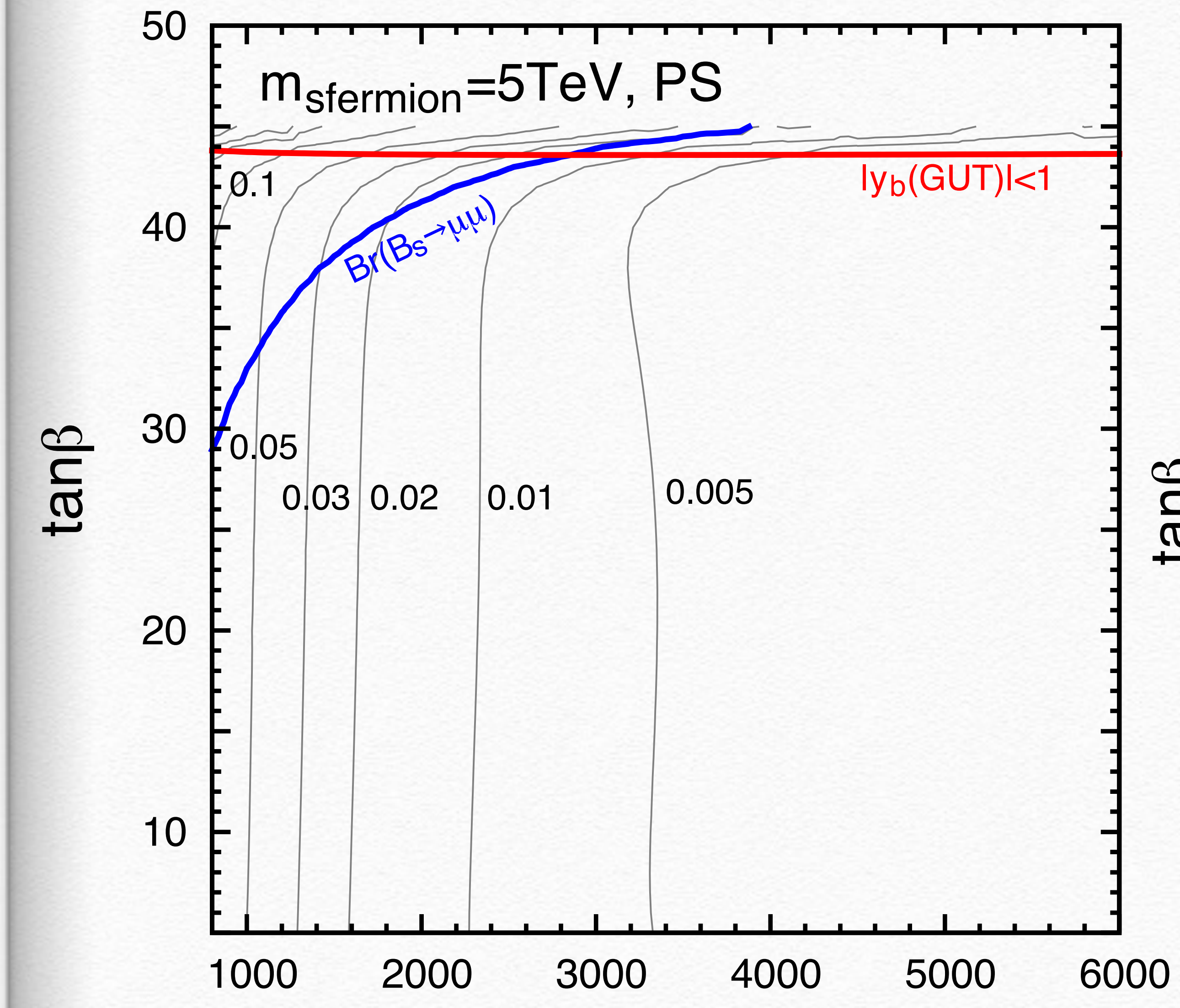
a parameter scan

Endo Moroi MMN

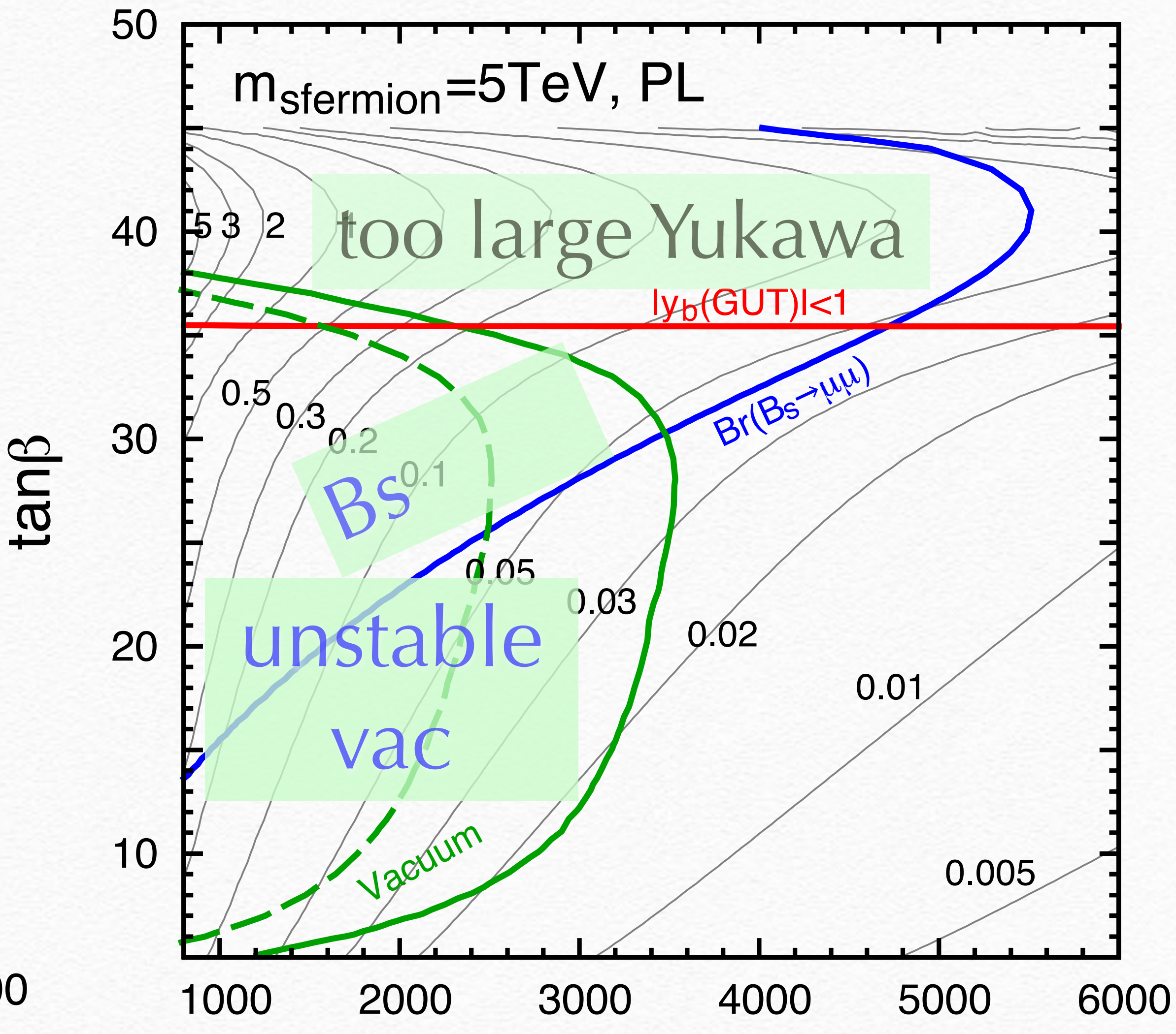
M3=-μ=m(sfermion) …….=5TeV

CCB vacuum constraint kill significant parameter space where ΔΓ(h→bb) is large

Small At>0



Large At>0



full parameter scan

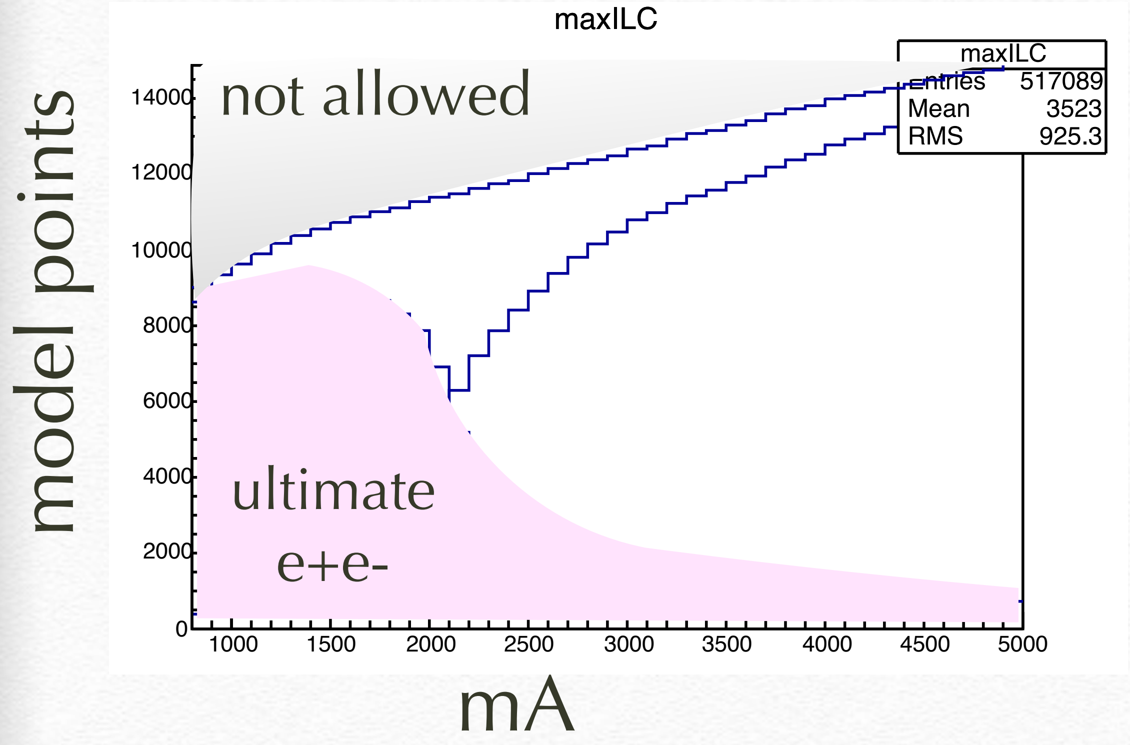
taken Universal because we are using SuperISO

- $m_{\tilde{Q}} = m_{\tilde{U}} = M_3 =$ 3, 4, and 5 TeV, does not matter except h→gg
- $m_{\tilde{D}} = m_{\tilde{L}} = m_{\tilde{E}} = \max(m_{\tilde{U}}, |\mu|)$,
- $A_t = A_t^{(\mathrm{NS})},\ A_t^{(\mathrm{NL})},\ A_t^{(\mathrm{PS})},\ A_t^{(\mathrm{PL})}$, scan over all four At solution
- $0.8\,\mathrm{TeV} < m_A < 6\,\mathrm{TeV}$,
- $-2 < \mu/m_{\tilde{U}} < -0.5$, or $0.5 < \mu/m_{\tilde{U}} < 2$
- $5 < \tan\beta < 50$.

Extensive Modification of FeynHiggs to assure decoupling limit including some bug fix+choice of wave function renormalization (at $p^2 = 0$) in higgs decay.
Our calculate include re-summation, higher order QCD
(Hope this will be one of official options of FeynHiggs)

accessibility to heavy higgs parameters

beyond mA>2000GeV, it is not easy to access deviation Endo Moroi, MMN



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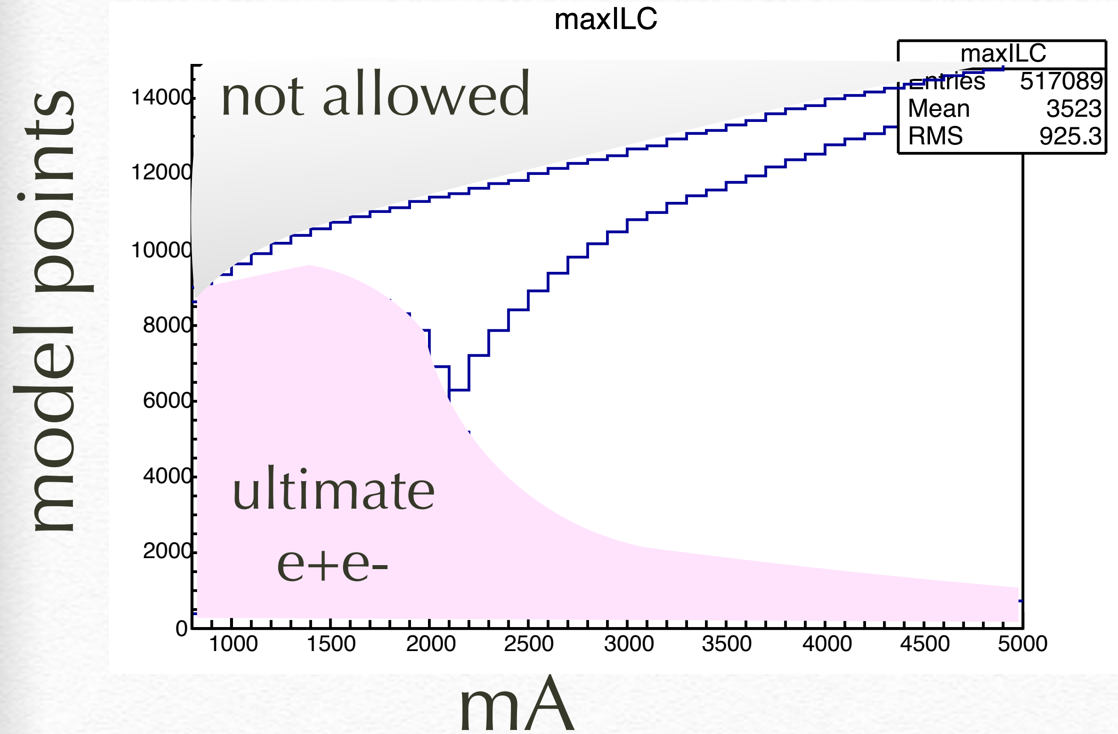
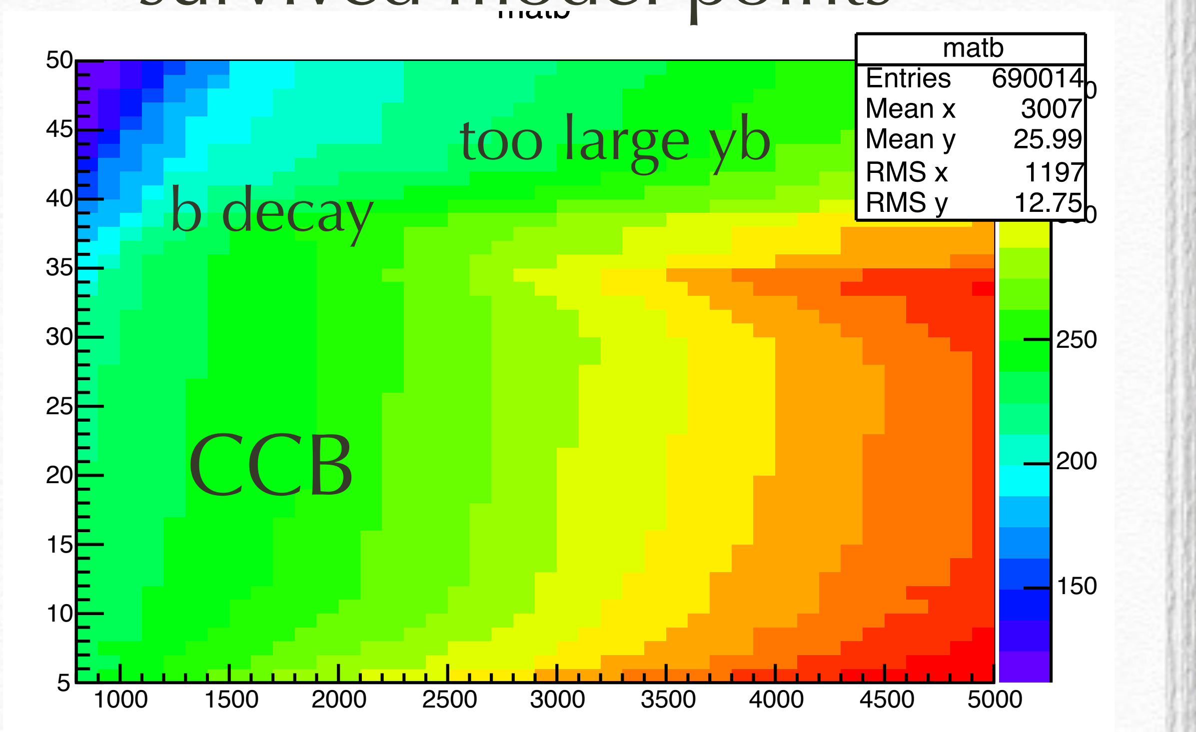
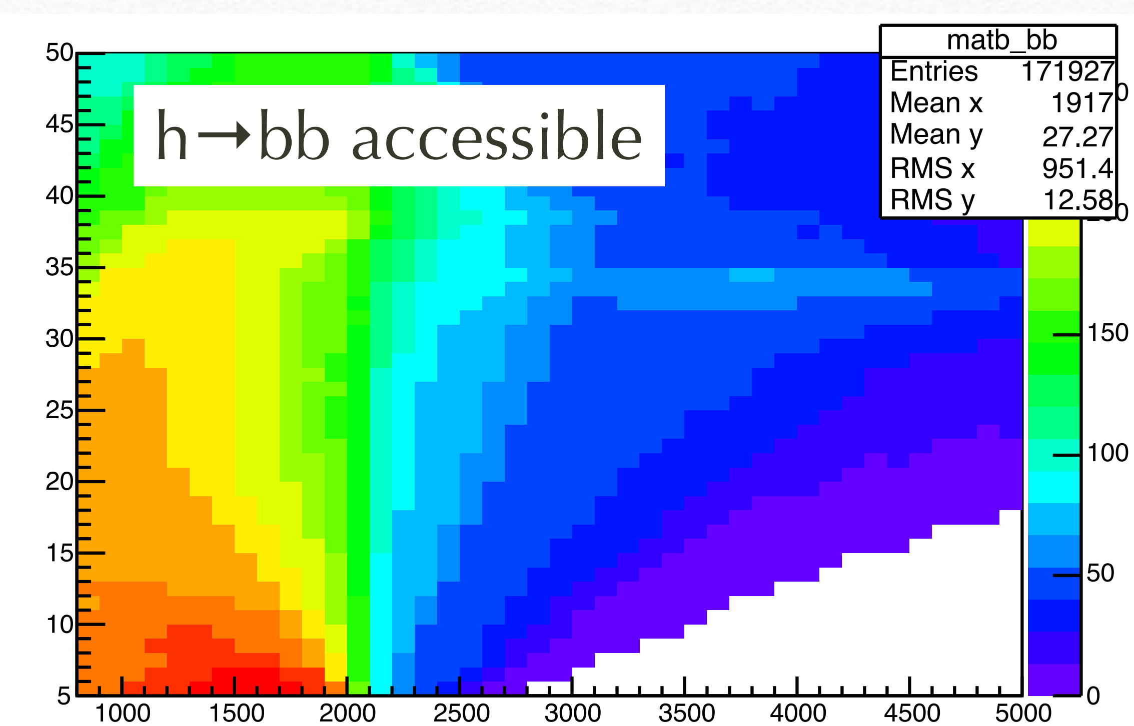
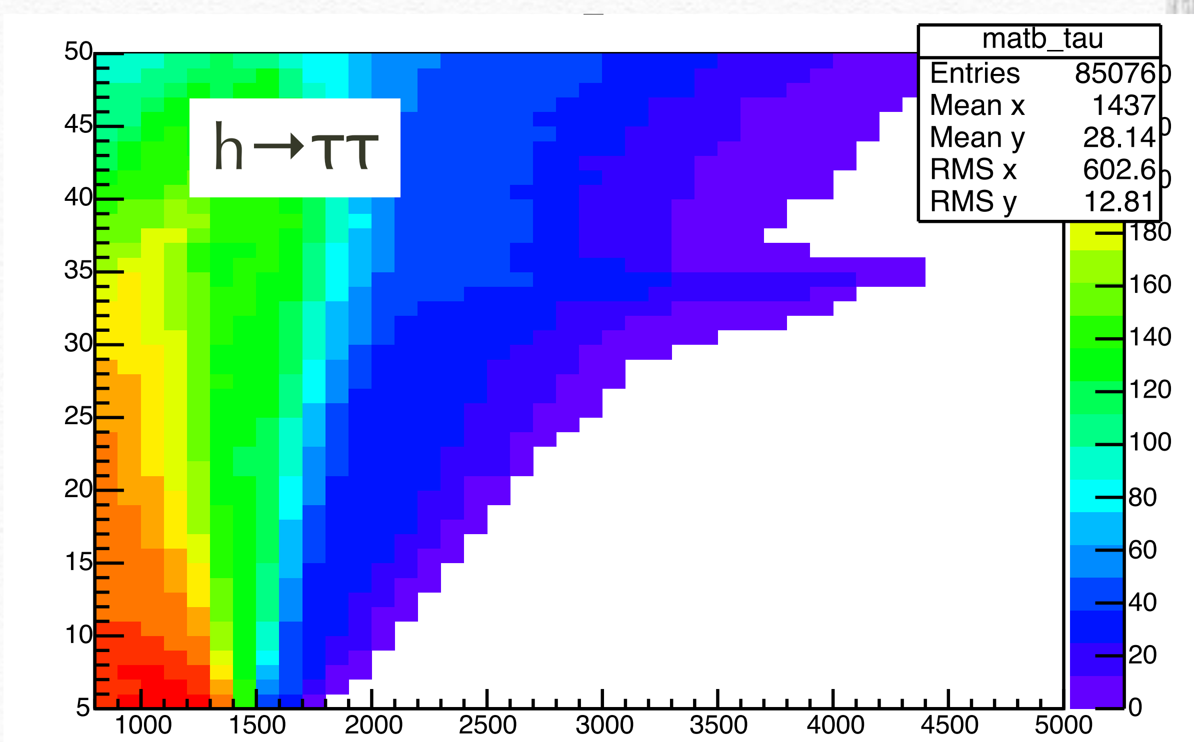


survived model points

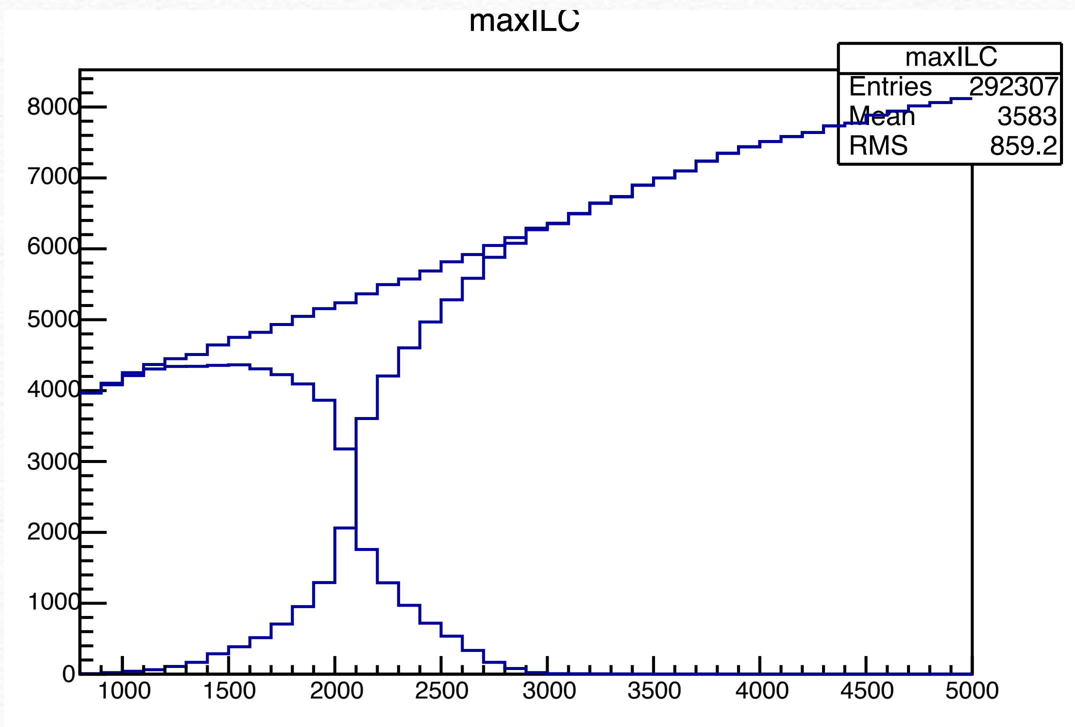




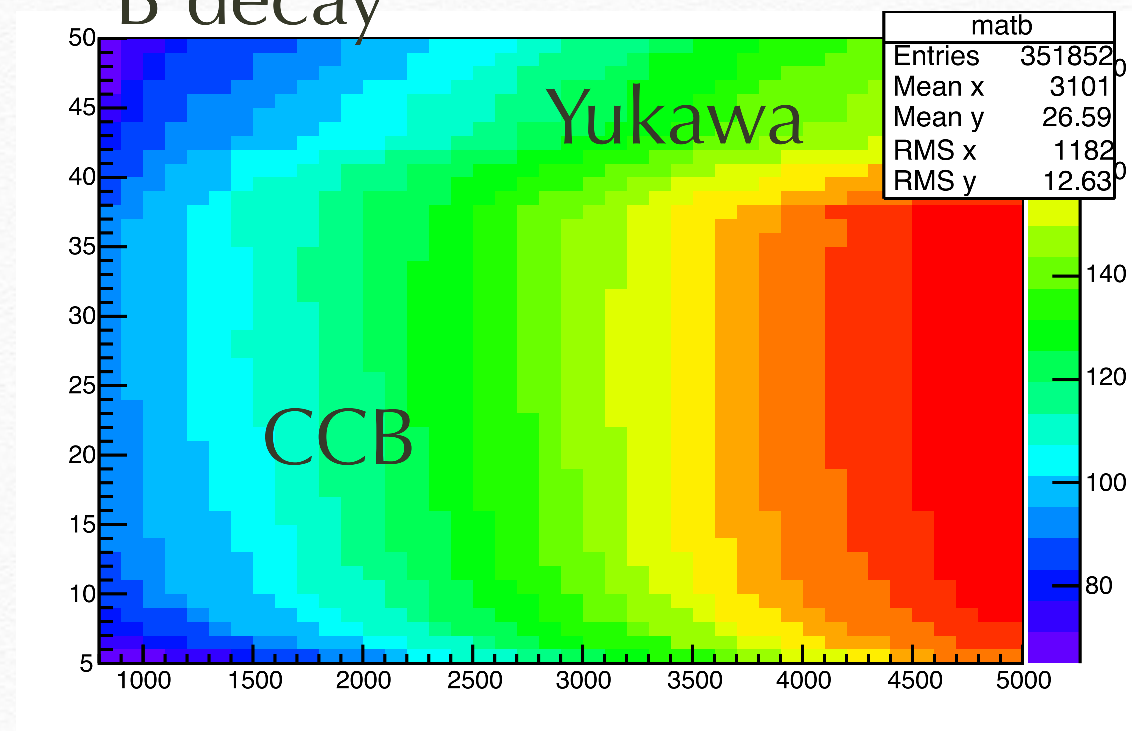


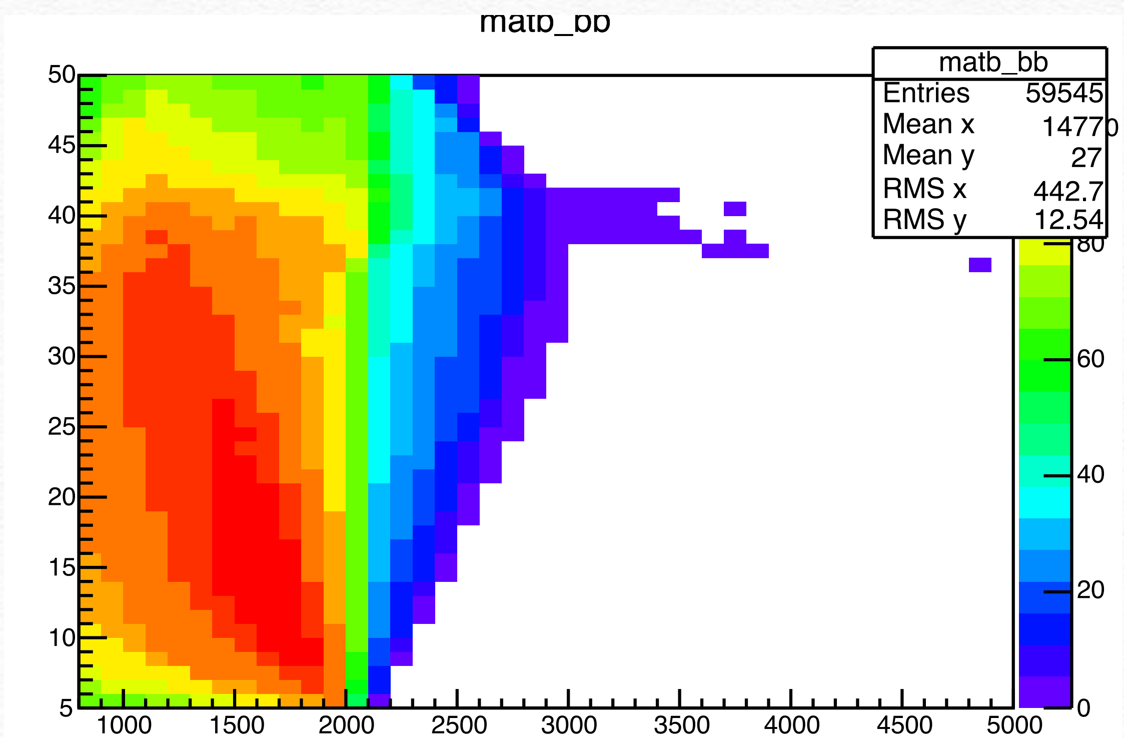
We found no deviation for h-> gg channel for Msusy>3000GeV

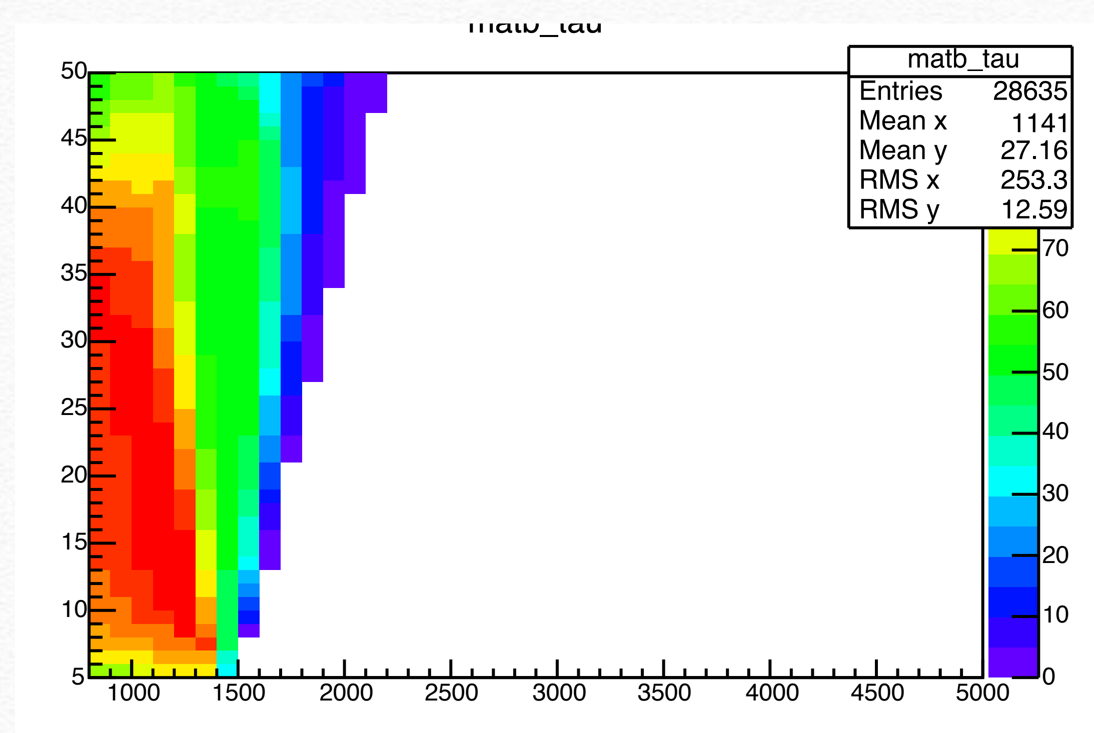
If no deeper minimum required



B decay

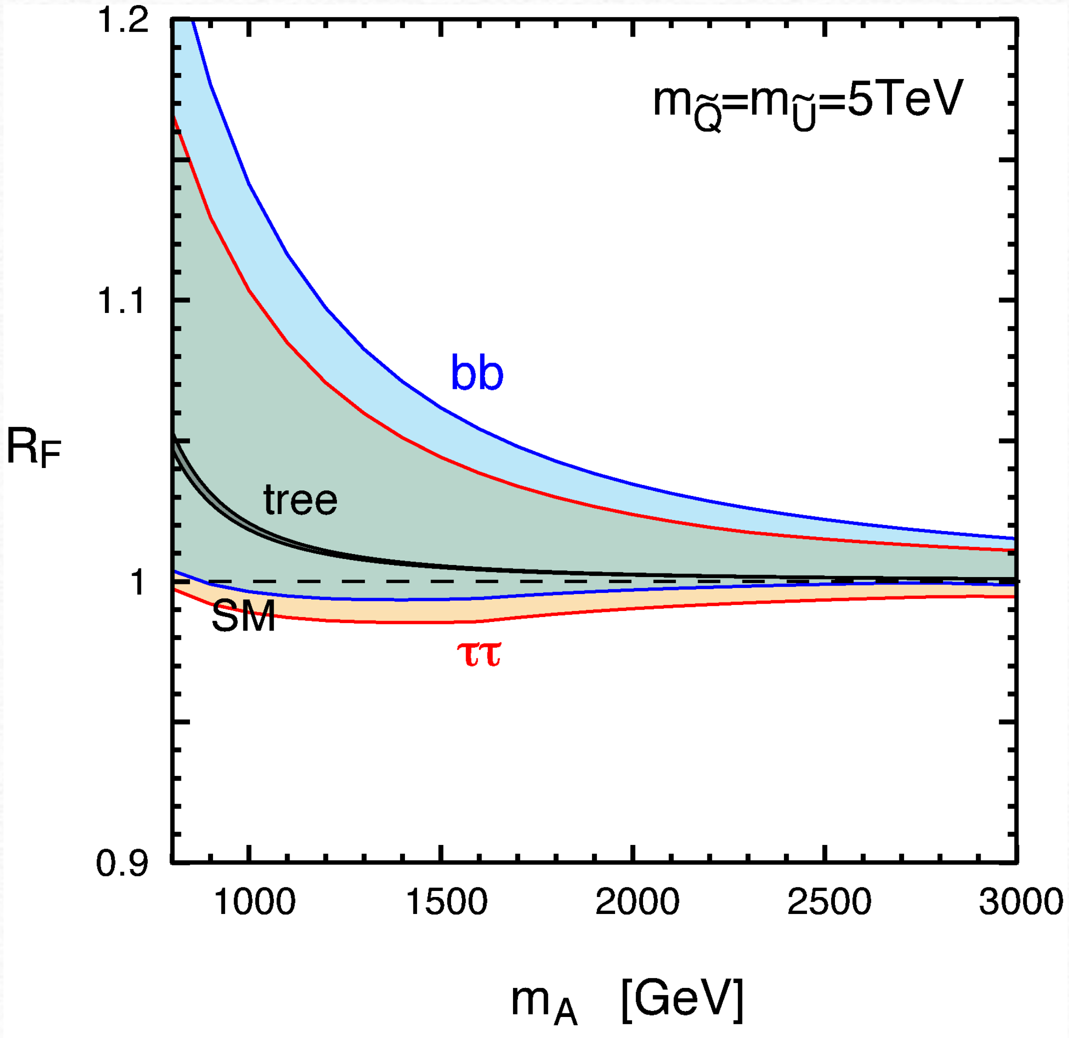




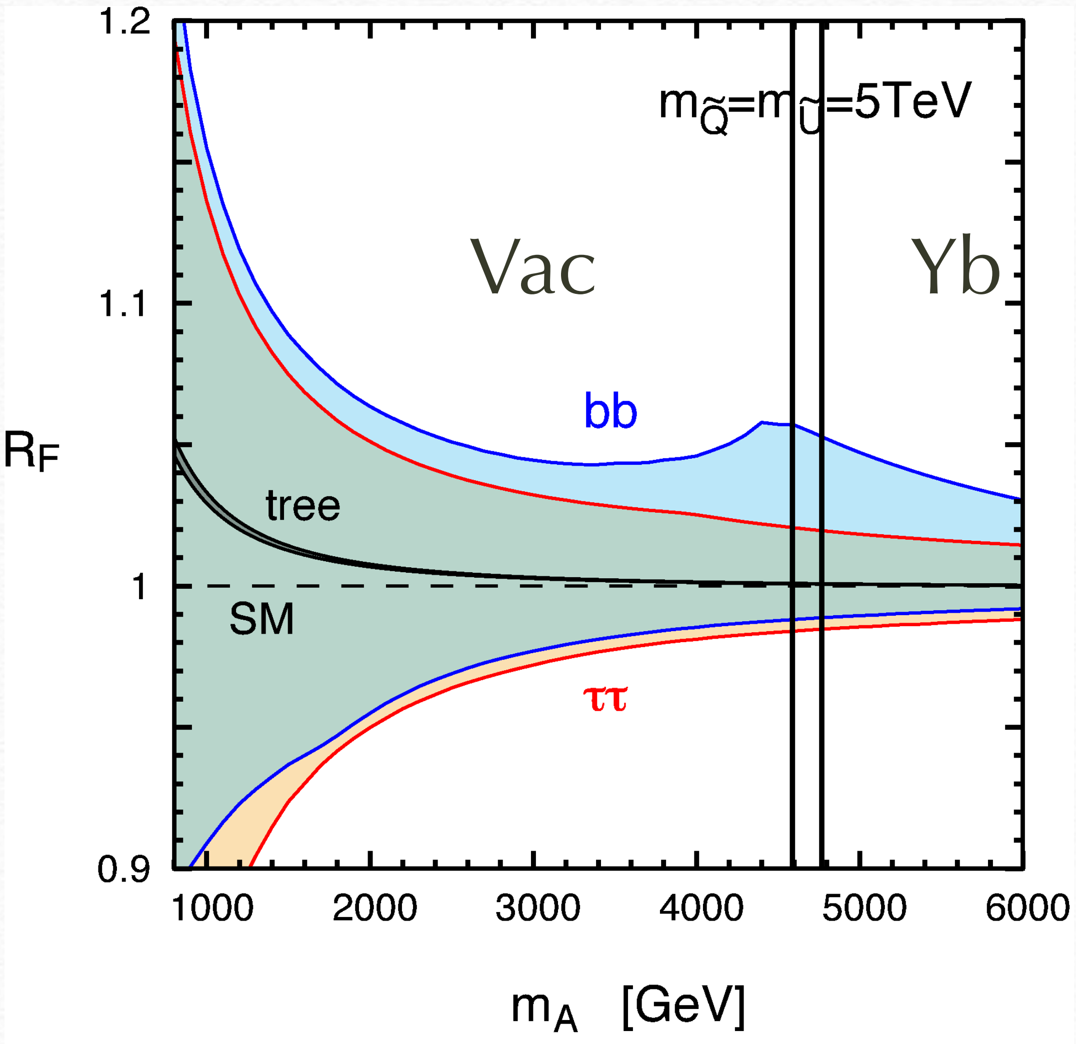


Upper limit of deviations and large At solutions

small AT solutions



All solutions

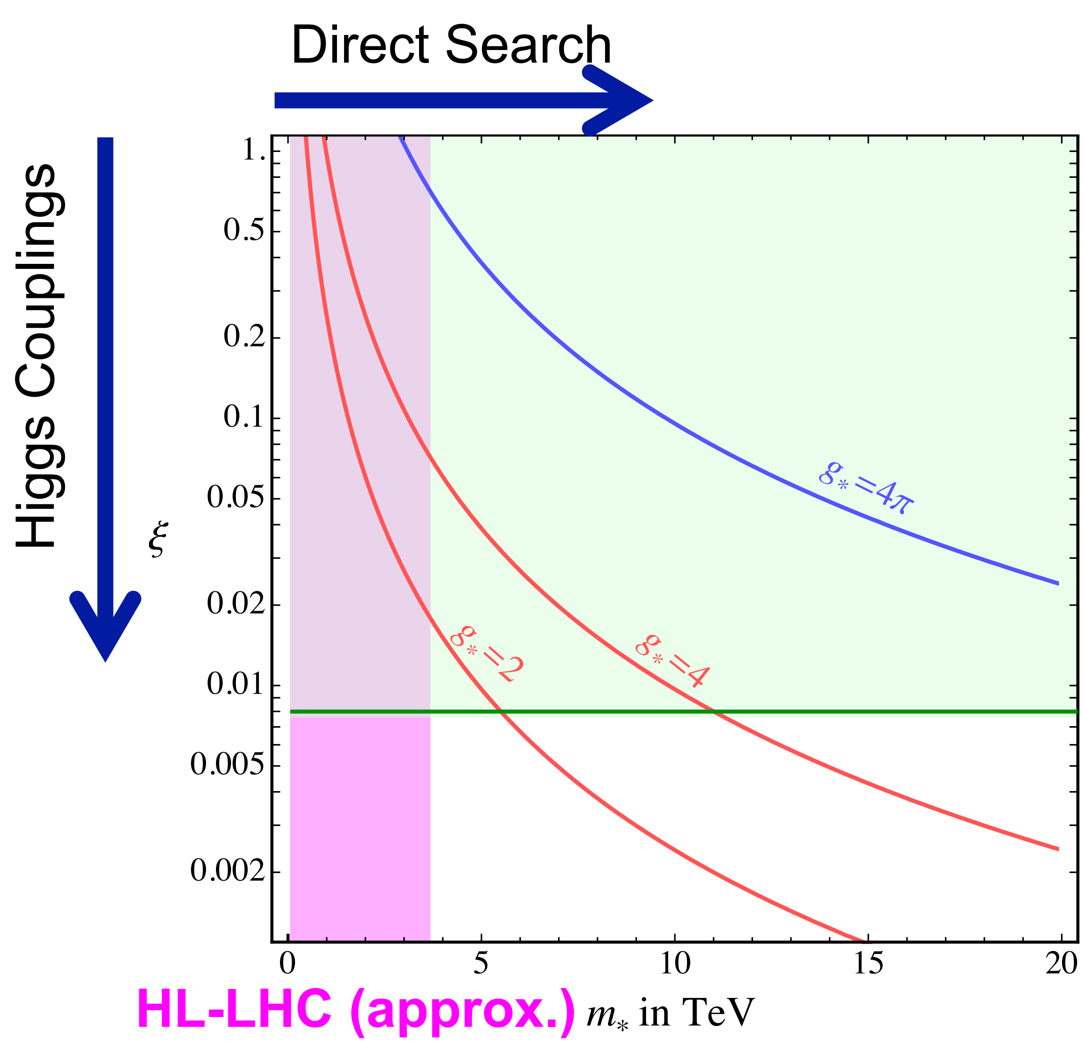


Summary

- MSSM Higgs sector is more constrained after Higgs discovery. Mh=fixed A
- control parameter $\Delta_b \rightarrow$ At, μ,
- B decay and CCB contraint (fragile)
  - Bs→μμ sensitive for non-universal squark mass
  - CCB vacua →tree level calculation. Inclusion of leading SUSY QCD correction is important.
- Need to pay attention if public packages are doing right job in several TeV range, and O(1%) deviation.

Minimal Composite Higgs Model

- Higgs boson from SO(5)→SO(4)
- Higgs boson～ PNG boson. Mass of the Higgs boson arise from correction of elementary sector.



Robust Correction to H→ ZZ

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \sqrt{1-\xi}$$

ILC

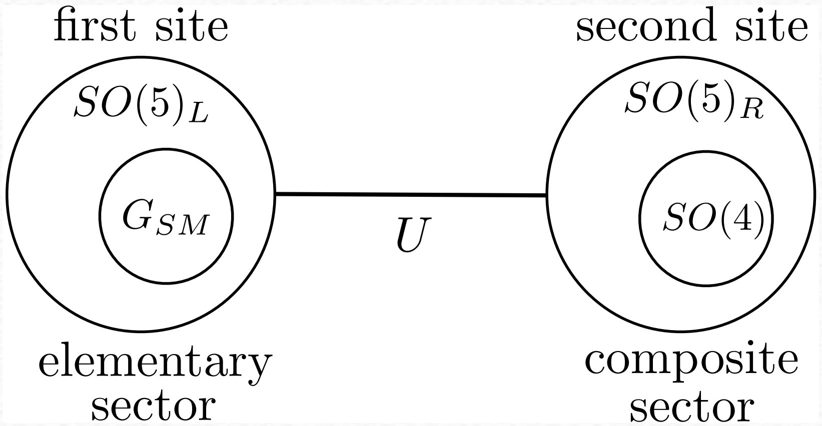
$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

Origin of Yukawa coupling

Composite state

$$\psi_u^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} B_u - X_u \\ -i(B_u + X_u) \\ T_u + U_u \\ i(T_u - U_u) \\ \sqrt{2}\tilde{T}_u \end{pmatrix}, \quad \psi_d^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} B_d - X_d \\ -i(B_d + X_d) \\ T_d + U_d \\ i(T_d - U_d) \\ \sqrt{2}\tilde{T}_d \end{pmatrix},$$

two site model

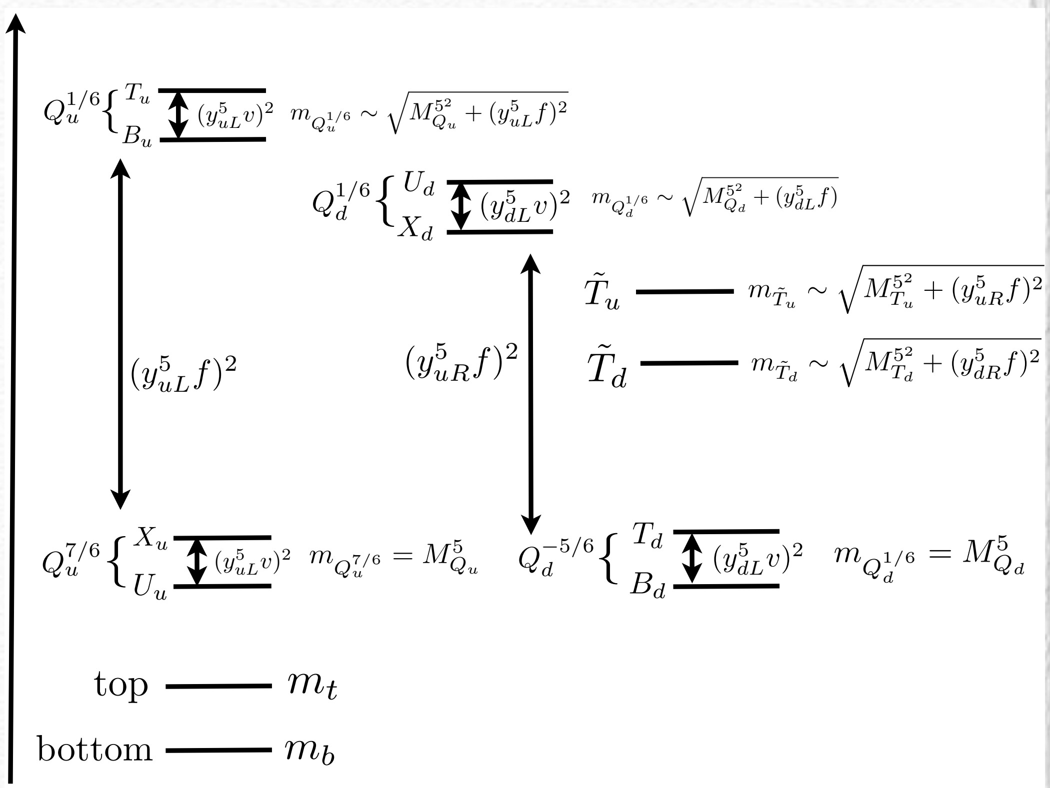


Elementary-Composite mixing

$$\mathcal{L}^5_{mix} = y^5_{uL} f (\bar{Q}^5_{uL})^I U_{IJ} {\psi^5_{uR}}^J + y^5_{uR} f (\bar{T}^5_R)^I U_{IJ} {\psi^5_{uL}}^J$$
$$+ y^5_{dL} f (\bar{Q}^5_{dL})^I U_{IJ} {\psi^5_{dR}}^J + y^5_{dR} f (\bar{B}^5_R)^I U_{IJ} {\psi^5_{dL}}^J + h.c,$$

Composite mass

$$\mathcal{L}^5_{mass} = -M^5_{Q_u} \bar{\tilde{Q}}_u \tilde{Q}_u - M^5_{T_u} \bar{\tilde{T}}_u \tilde{T}_u - M^5_{Q_d} \bar{\tilde{Q}}_d \tilde{Q}_d - M^5_{T_d} \bar{\tilde{T}}_d \tilde{T}_d + h.c$$



- Higgs boson does not have direct hff coupling
- Composite fermions mix to the elementary sector inducing Yukawa coupling. (top partner , bottom partners) → corrections

Higgs to Fermion...

Kubota Nojiri to appear

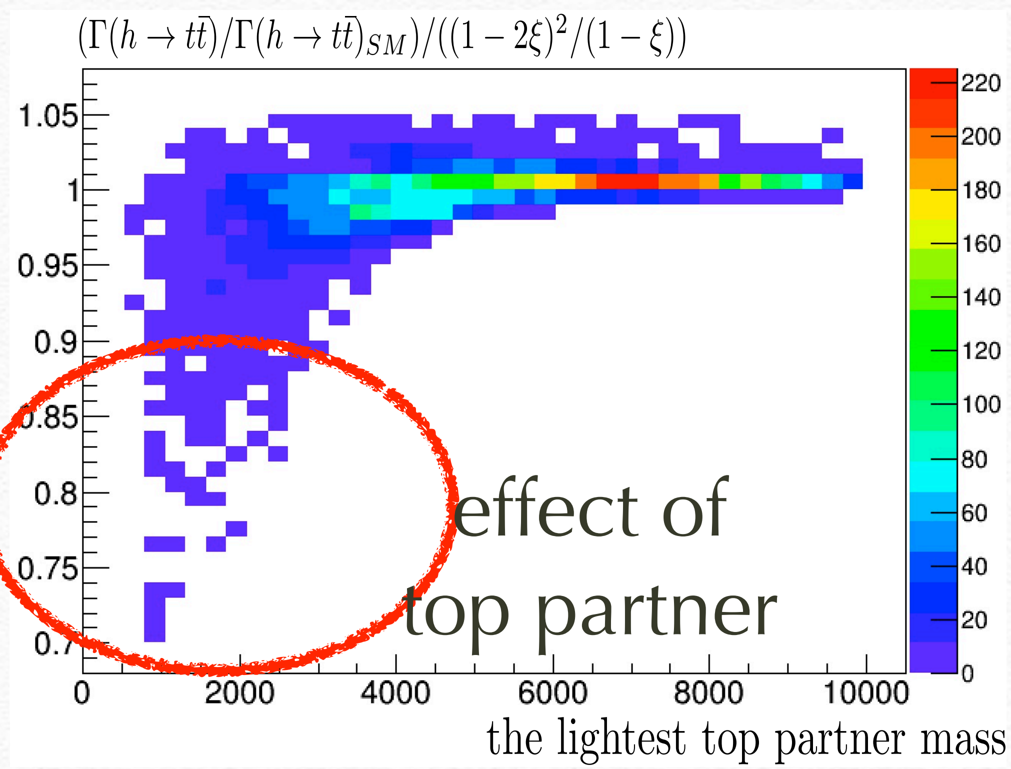
top and bottom Yukawa coupling correction

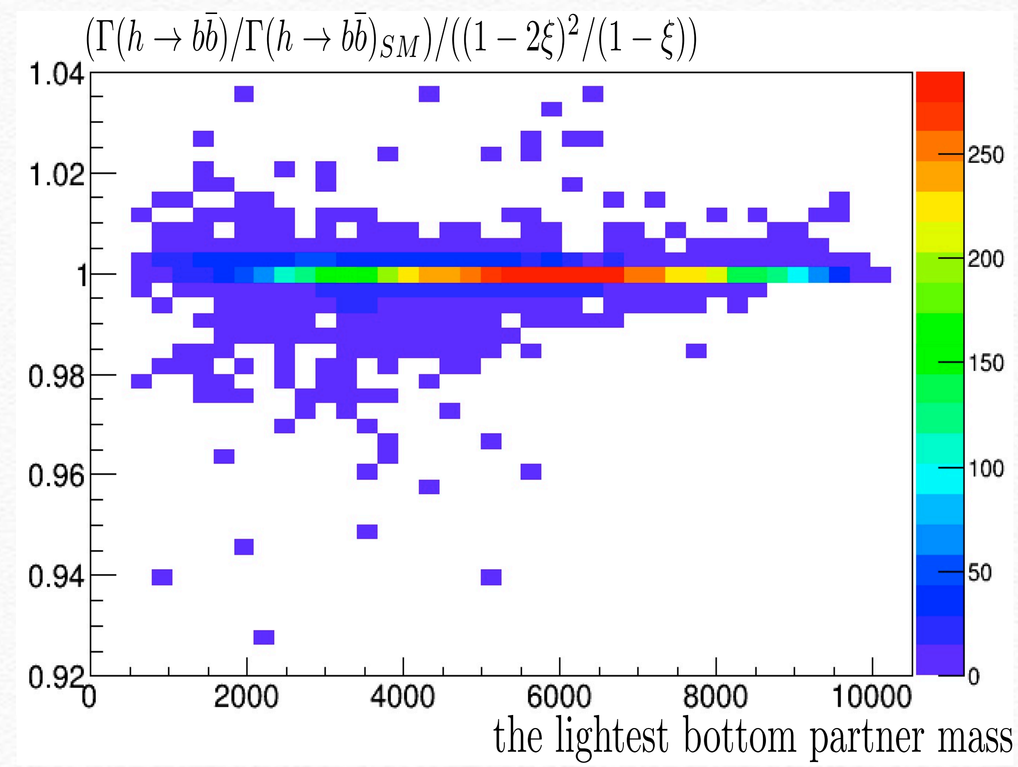
$$\frac{y_u^5}{m_u^5} = \frac{1}{m_u^5}\frac{\partial m_u^5}{\partial v} = \frac{2}{f\tan(2v/f)} + \frac{f}{2Z_q^5 Z_{u_R}^5}\sin(2v/f)\Big[\Big(\frac{1}{|M_{u_4}^5|^2} - \frac{1}{|M_{u_1}^5|^2}\Big)(|y_{uL}^5|^2/2 - |y_{uR}^5|^2) + \Big(\frac{1}{|M_{d_4}^5|^2} - \frac{1}{|M_{d_1}^5|^2}\Big)|y_{dL}^5|^2/2 - \frac{f^2|y_{uR}^5|^2}{2}\Big(\frac{1}{|M_{u_4}^5|^2} - \frac{1}{|M_{u_1}^5|^2}\Big)\Big(\frac{|y_{uL}^5|^2}{|M_{u_4}^5|^2} + \frac{|y_{dL}^5|^2}{|M_{d_4}^5|^2}\Big)\Big],$$

leading terms can be estimated by ξ

5 representation model

$g_{htt}{}^2/\ [(1-2\xi)^2/(1-\xi)]$ $\qquad$ $g_{hbb}{}^2/[(1-2\xi)^2/(1-\xi)]$





Higgs to Fermion…

Kubota Nojiri to appear

top and bottom Yukawa coupling correction

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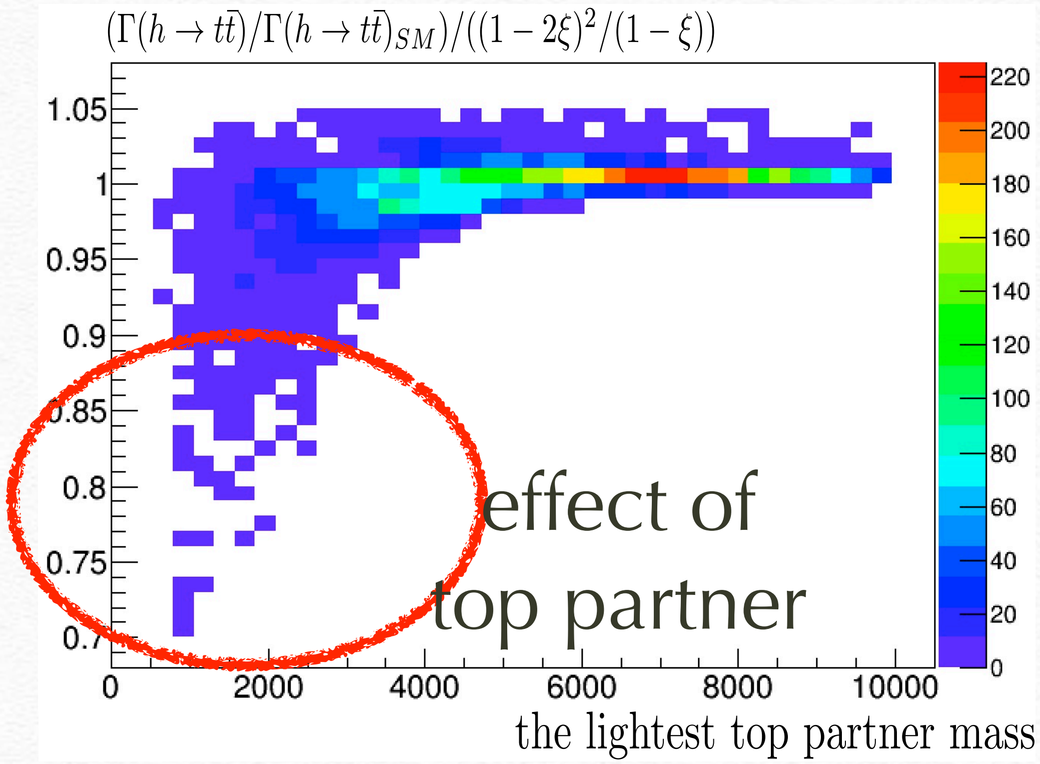
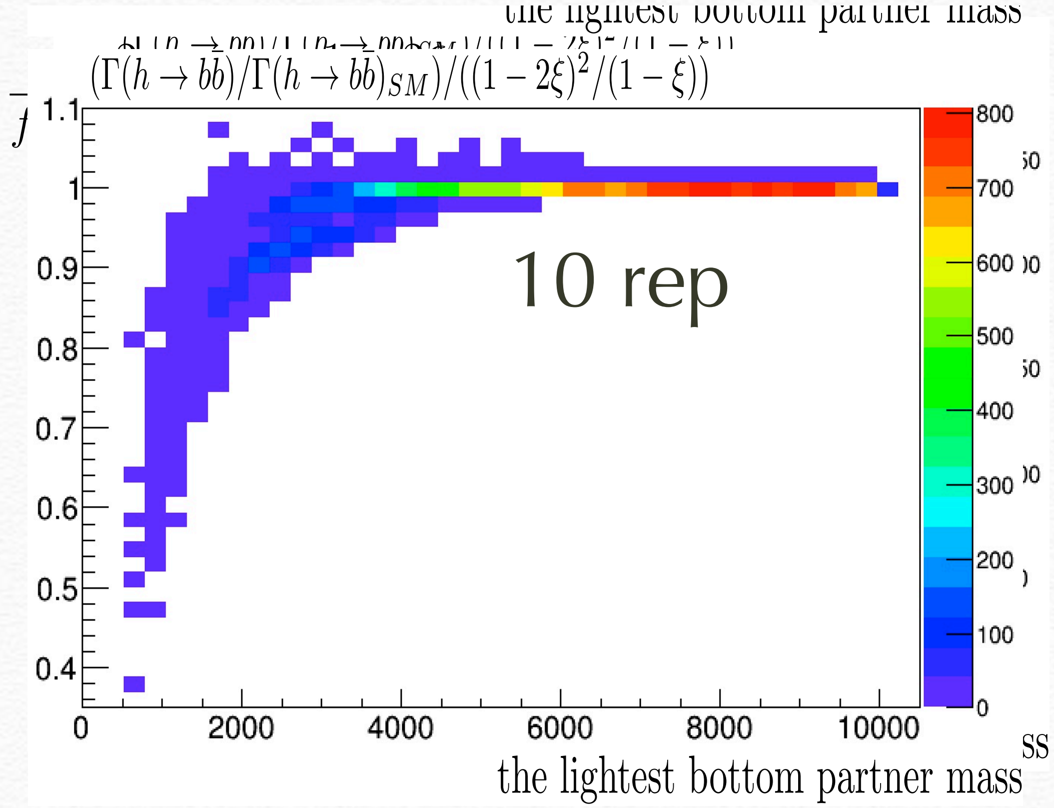
leading terms can be estimated by ξ

5 representation model

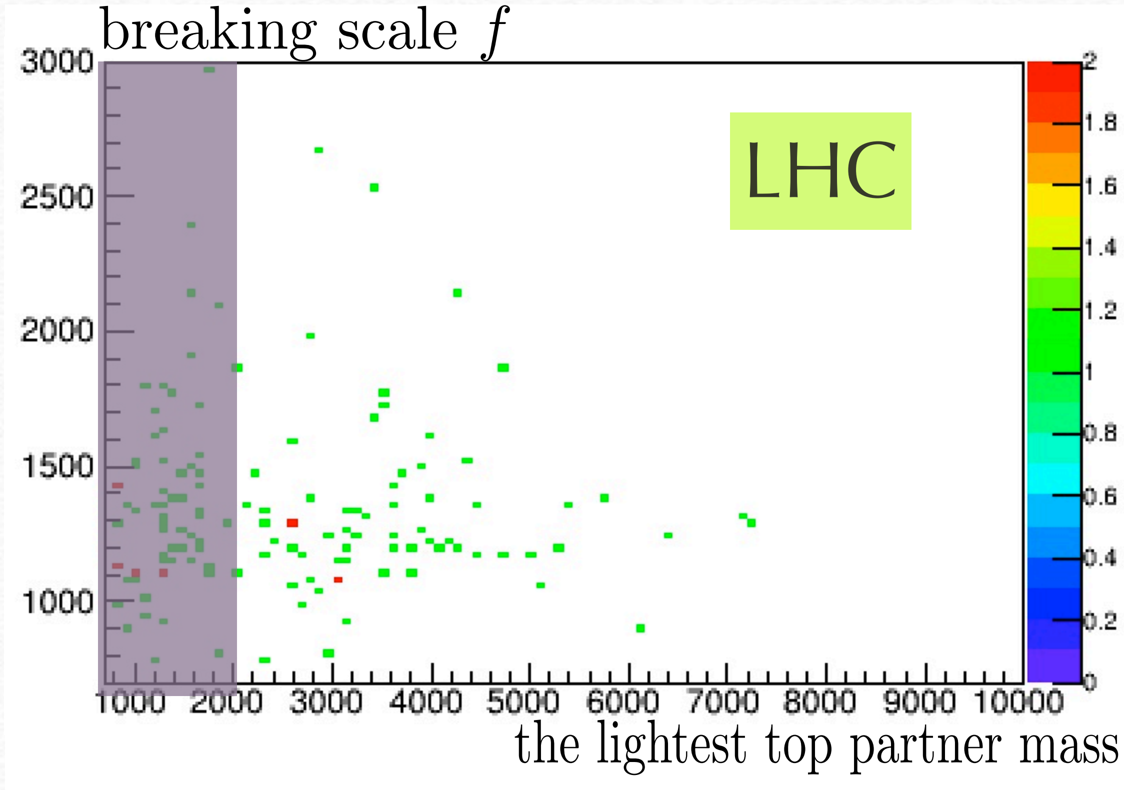
$g_{htt}{}^2/ [(1-2\xi)^2 /(1-\xi)]$ $g_{hbb}{}^2 /[(1-2\xi)^2 /(1-\xi)]$

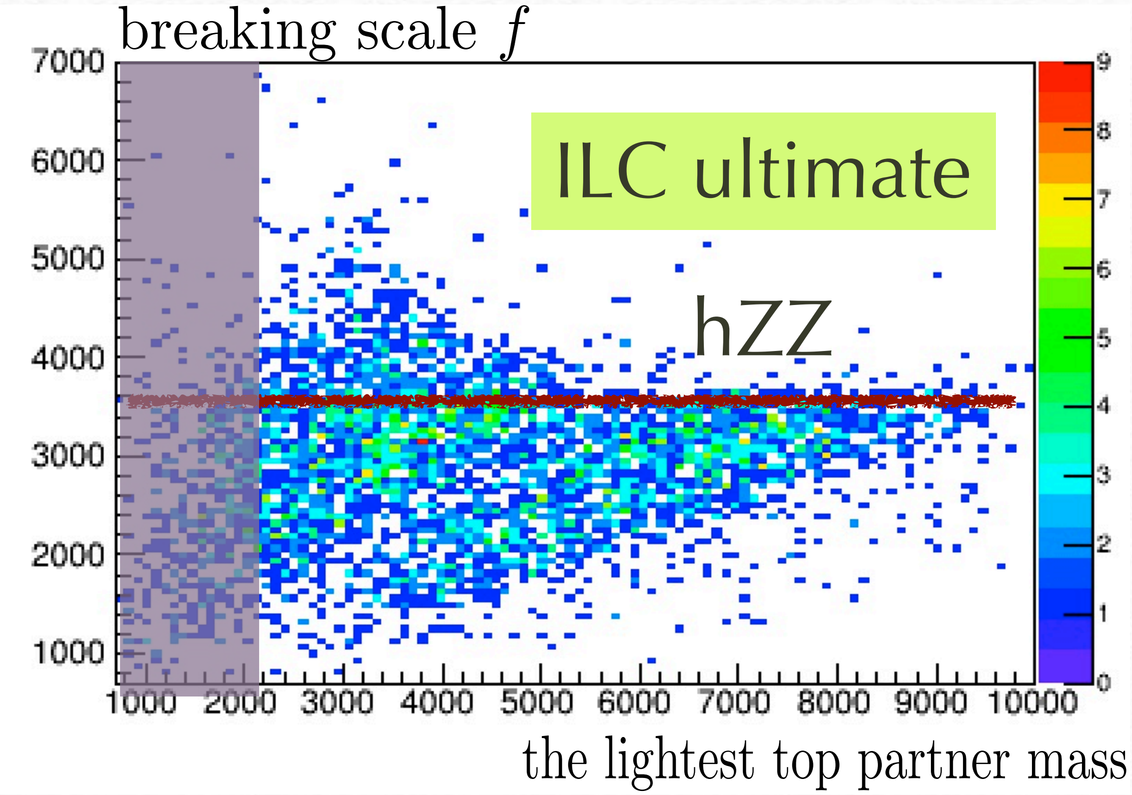




LHC vs ILC on accessibility Higgs coupling only

Kubota Nojiri to appear





Direct search at the Hadron Collider

Cross section based estimate

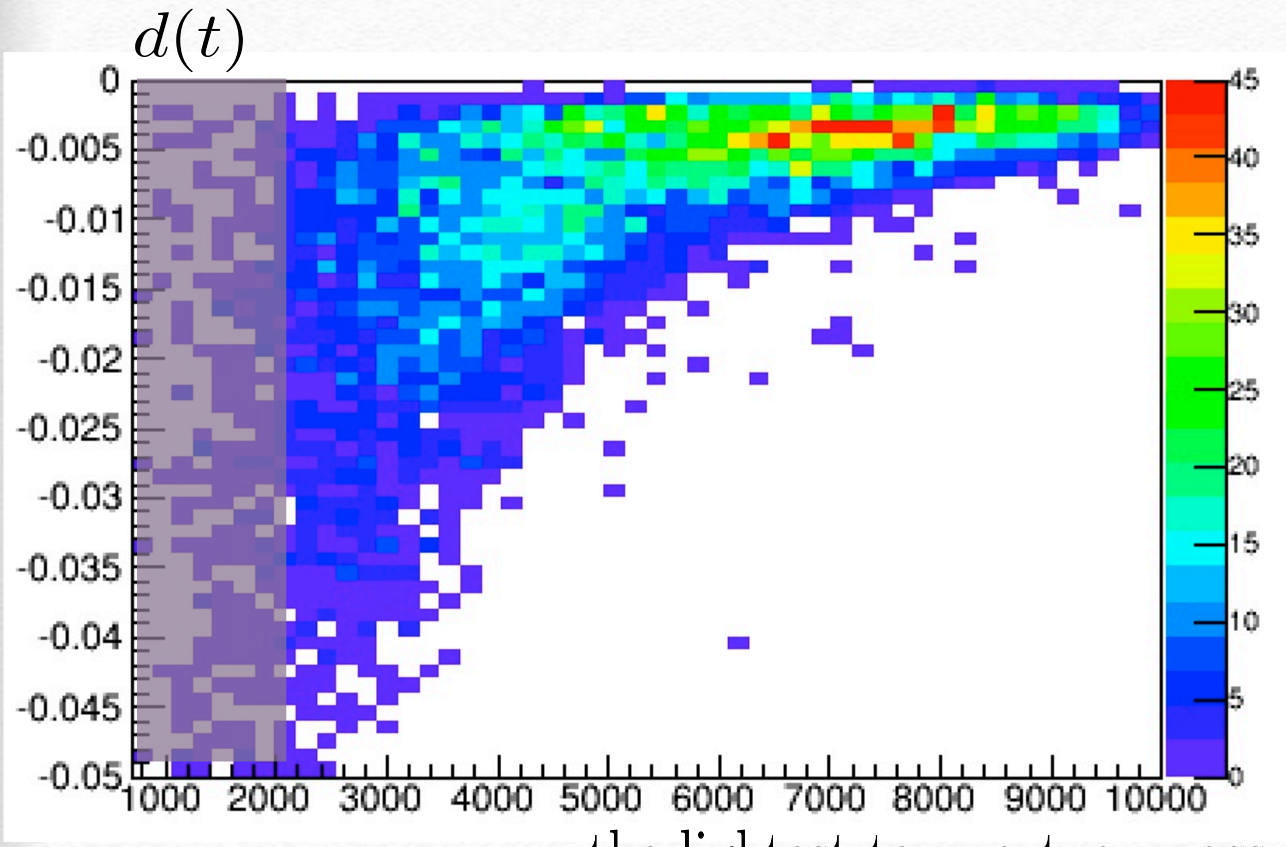
mX~ 2TeV at 14TeV

mX~7TeV at 100TeV

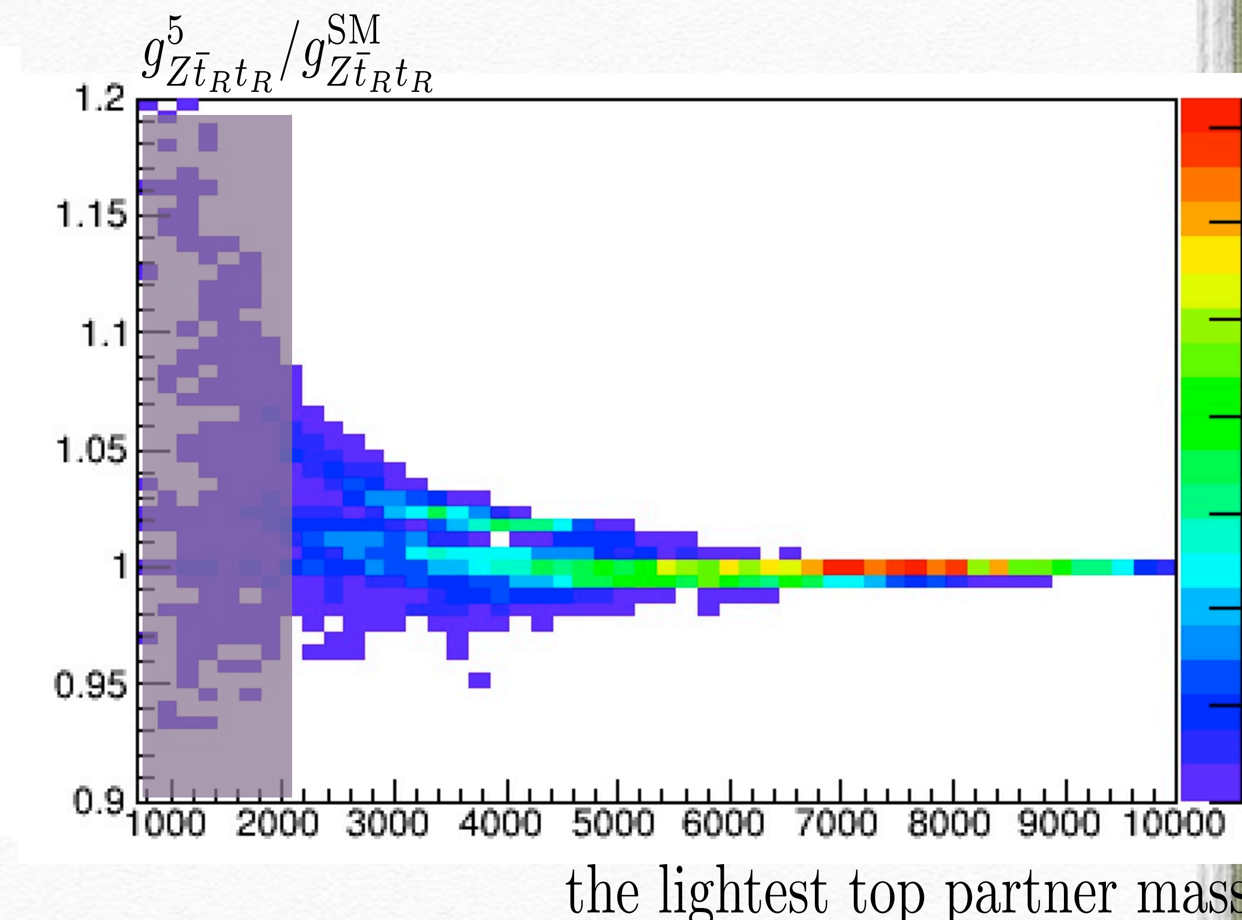
sigle production mX~12 TeV at 100TeV

ttH vs ttZ

top Yukawa coupling



ttZ(R) coupling



Relatively large correction to the top quark of order of 5% for both

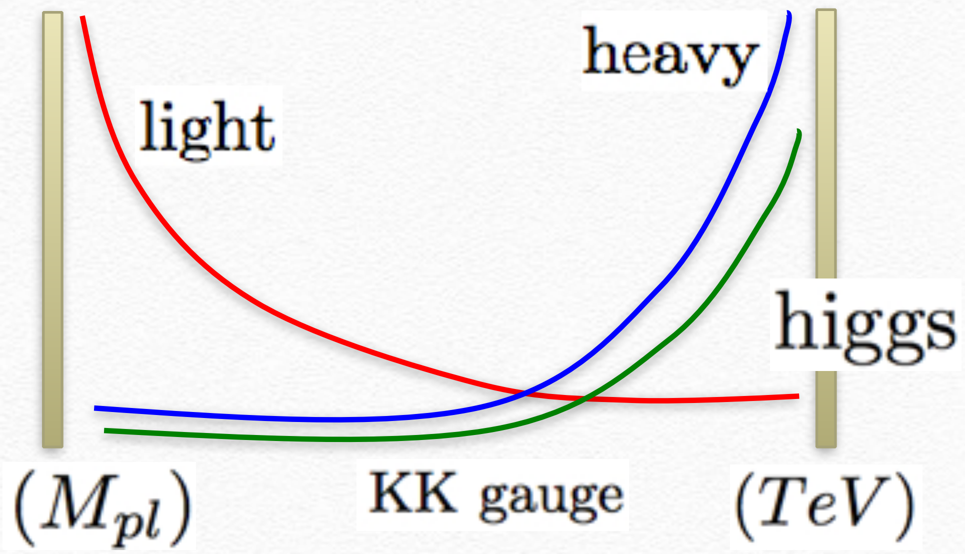
σ(ttZ)/σ(ttH) at VLHC?

RS model

$$ds^2 = e^{-2(kr_c\pi + F(x,\phi))}\eta_{\mu\nu}dx^\mu dx^\nu - r_c(1+2F(x,\phi))^2 d\phi^2$$

warp factor

radion



- 5 dim model but 5th dimension is not flat.
- All mass parameters are at Planck scale but Higgs boson on IR brane has light mass. warp factor
- matter and gauge boson in the bulk. bulk mass-> wave function profile
- Large KK corrections to loop process because KK modes live near IR brane. negative correction to gg→h
- Radion Higgs mixing : enhancement of γγ gg final state

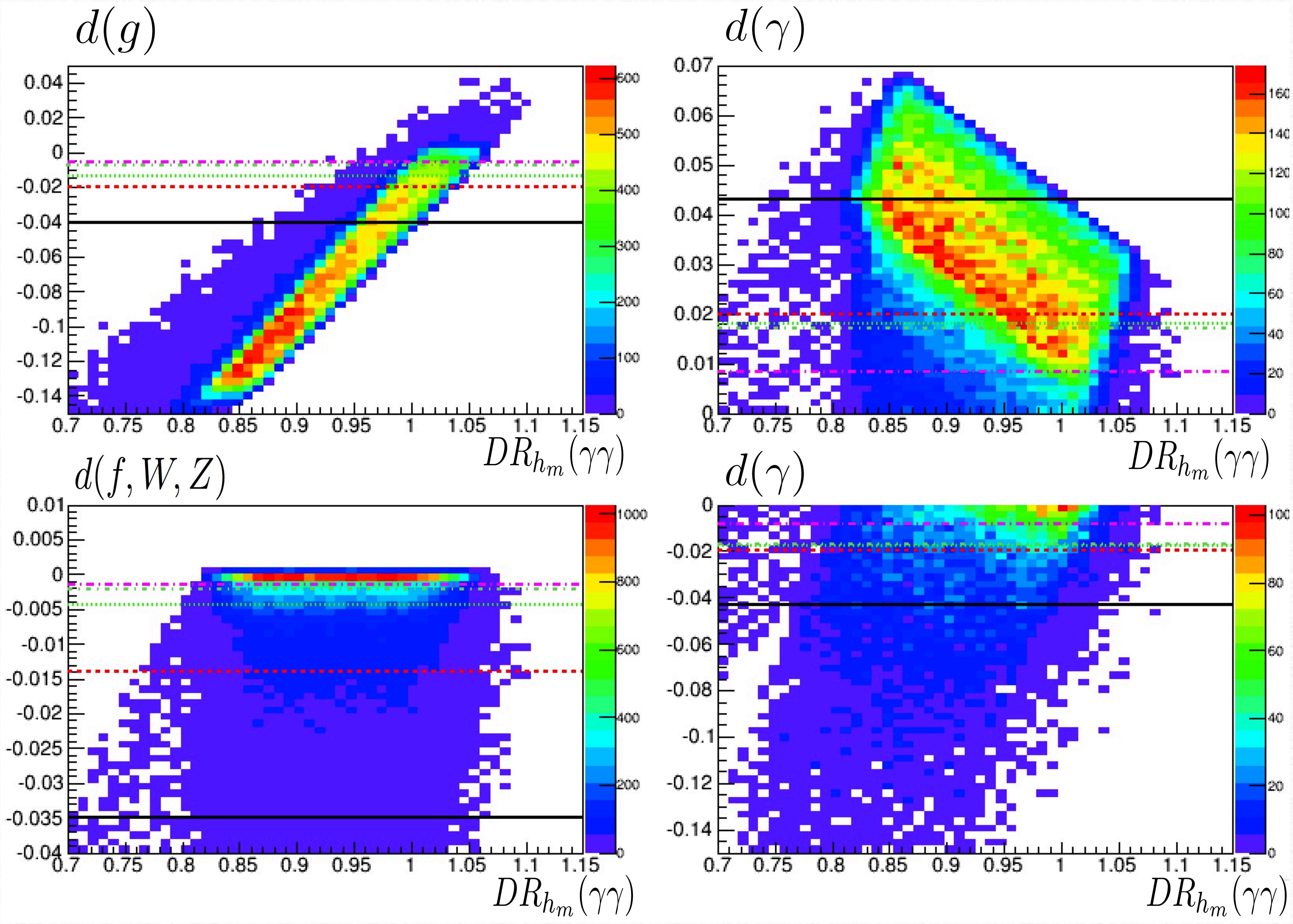


FIG. 7: Distributions of our model points in $DR_{h_m}(\gamma\gamma)$-$d(A)$ plane, where $d(A)$ is (a) $d(g)$, (b) $d(f,W,Z)$, (c) $d(\gamma)$ with $d(\gamma) > 0$ and (d) $d(\gamma)$ with $d(\gamma) < 0$. Expected 1σ sensitivity of the each coupling is also shown in the figure(see text).

maximal deviation of the couplings

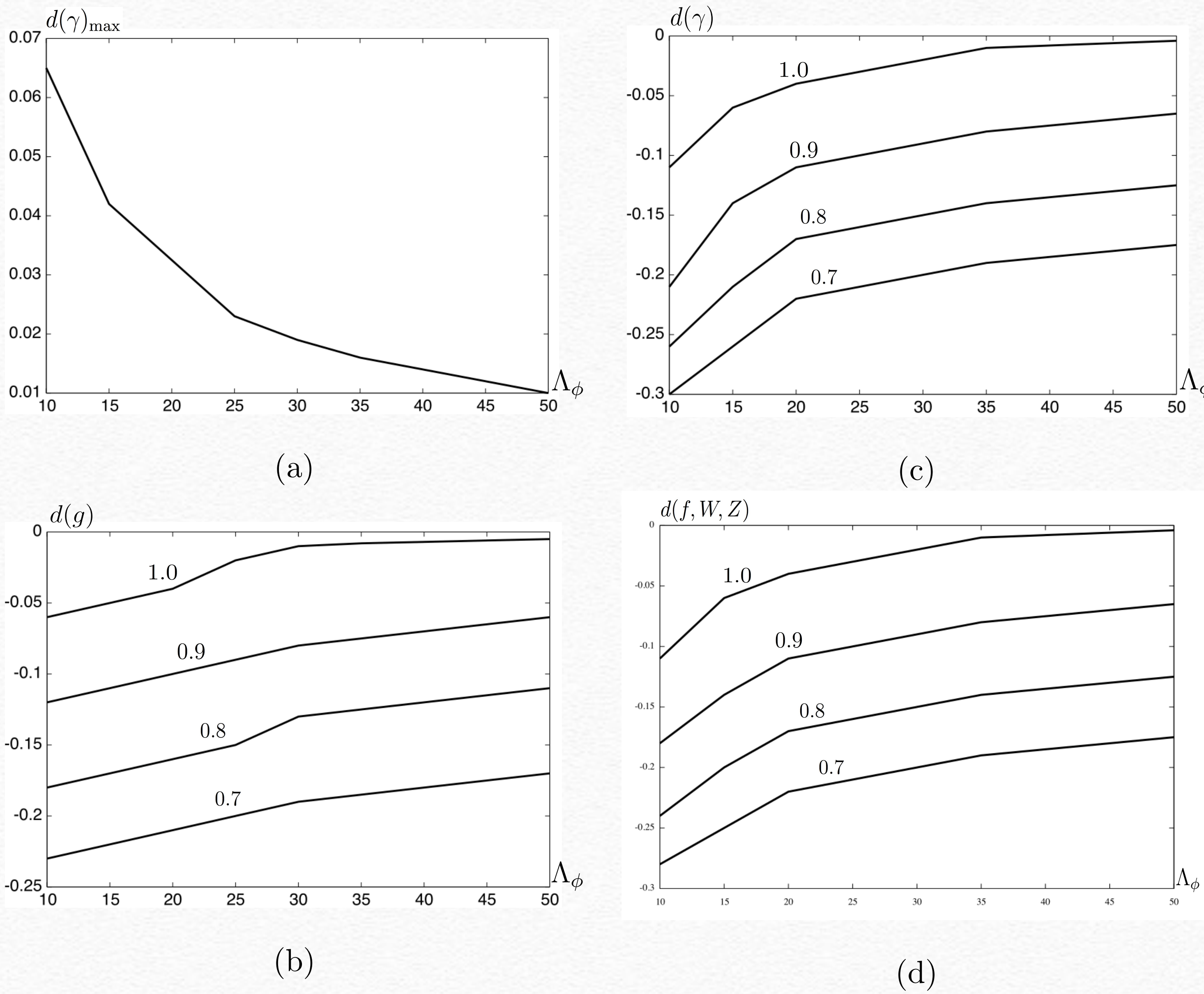


FIG. 4: The maximal deviations of $d(A)$, where d(A) is (a) $d(\gamma) > 0$, (b) $d(g)$, (c) $d(\gamma)$ and (a) $d(f, W, Z)$ vs Λ_ϕ at $DR_{h_m}(\gamma\gamma) = 0.7, 0.8, 0.9, 1.0$.