Higgs が見えなくなる理論的可能性

戸部和弘（東北大学）

LHCが切り拓く新しい素粒子物理学@ University of Tokyo

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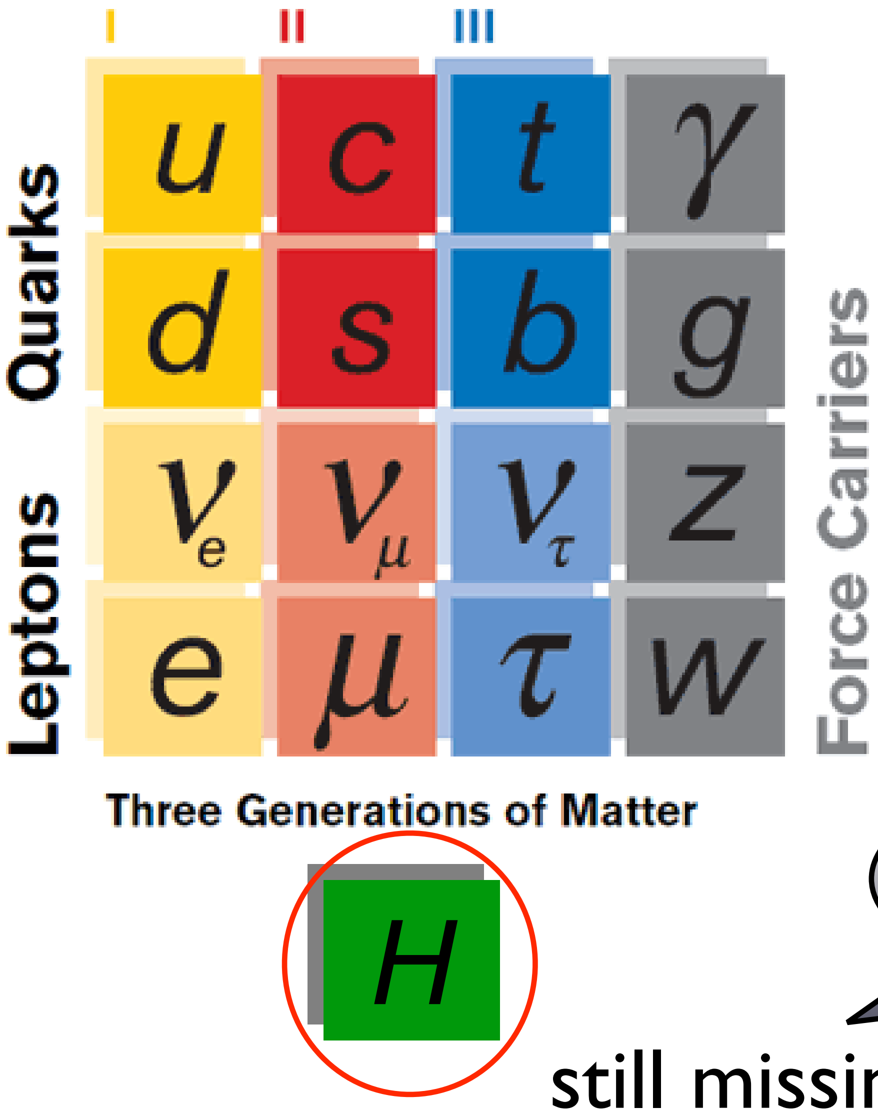
Introduction



Standard Model

SM is a successful theory,
but Higgs boson is still missing...

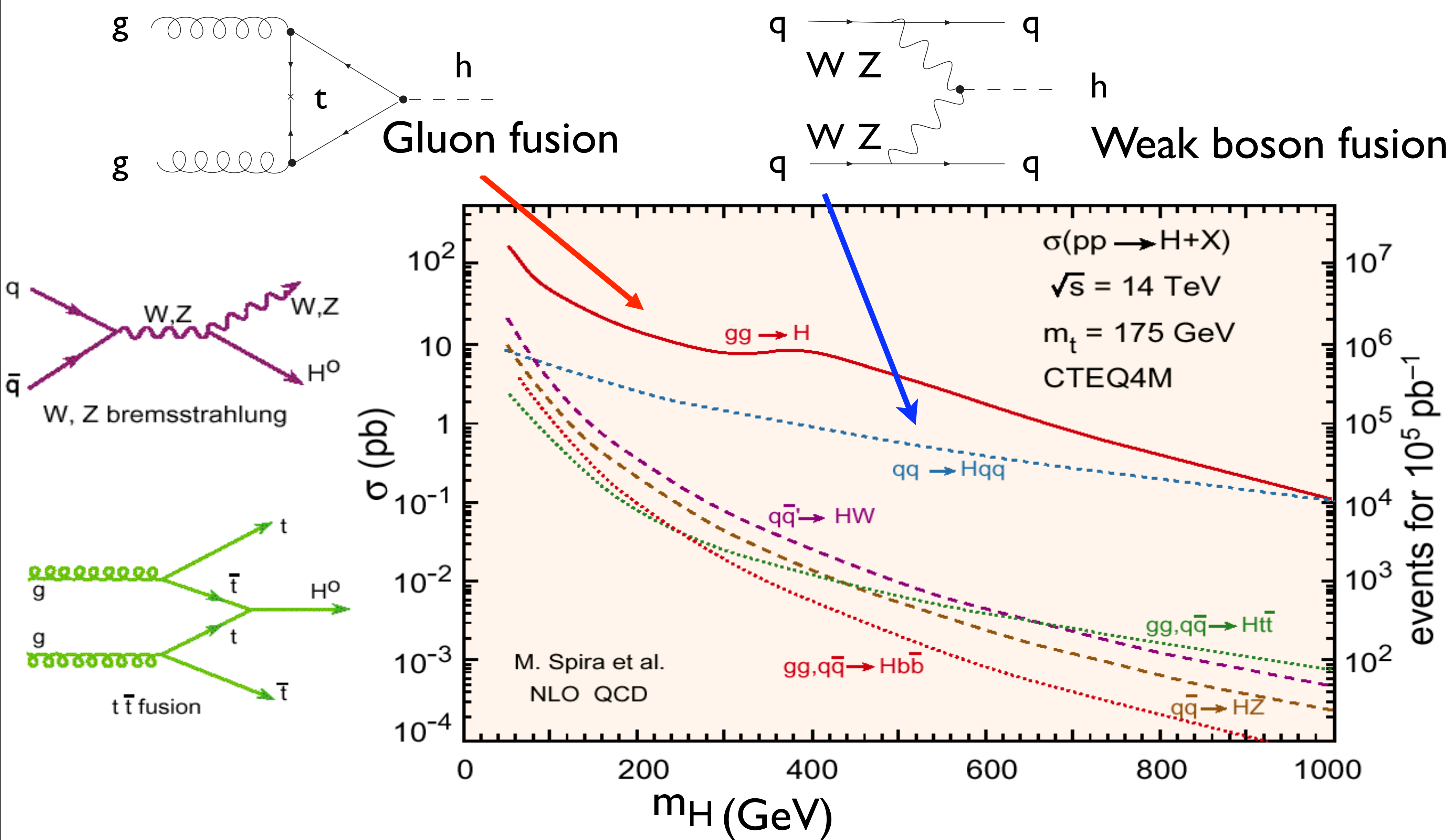
EW symmetry breaking?
Origin of particle masses?

still missing!

At LHC, we have a good chance to discover Higgs boson!

SM Higgs boson search at LHC

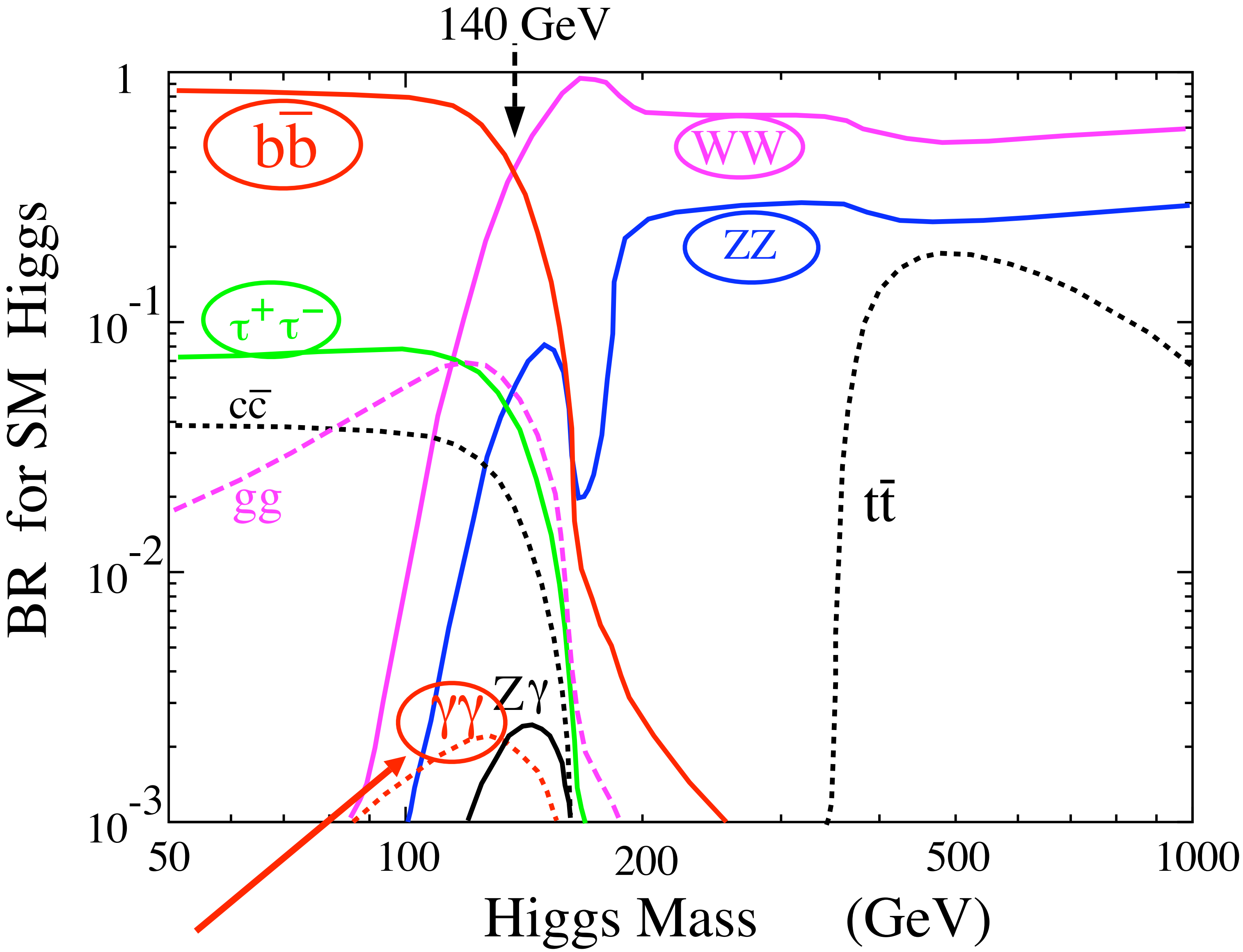
SM Higgs production at LHC....



gluon fusion is induced by top loop

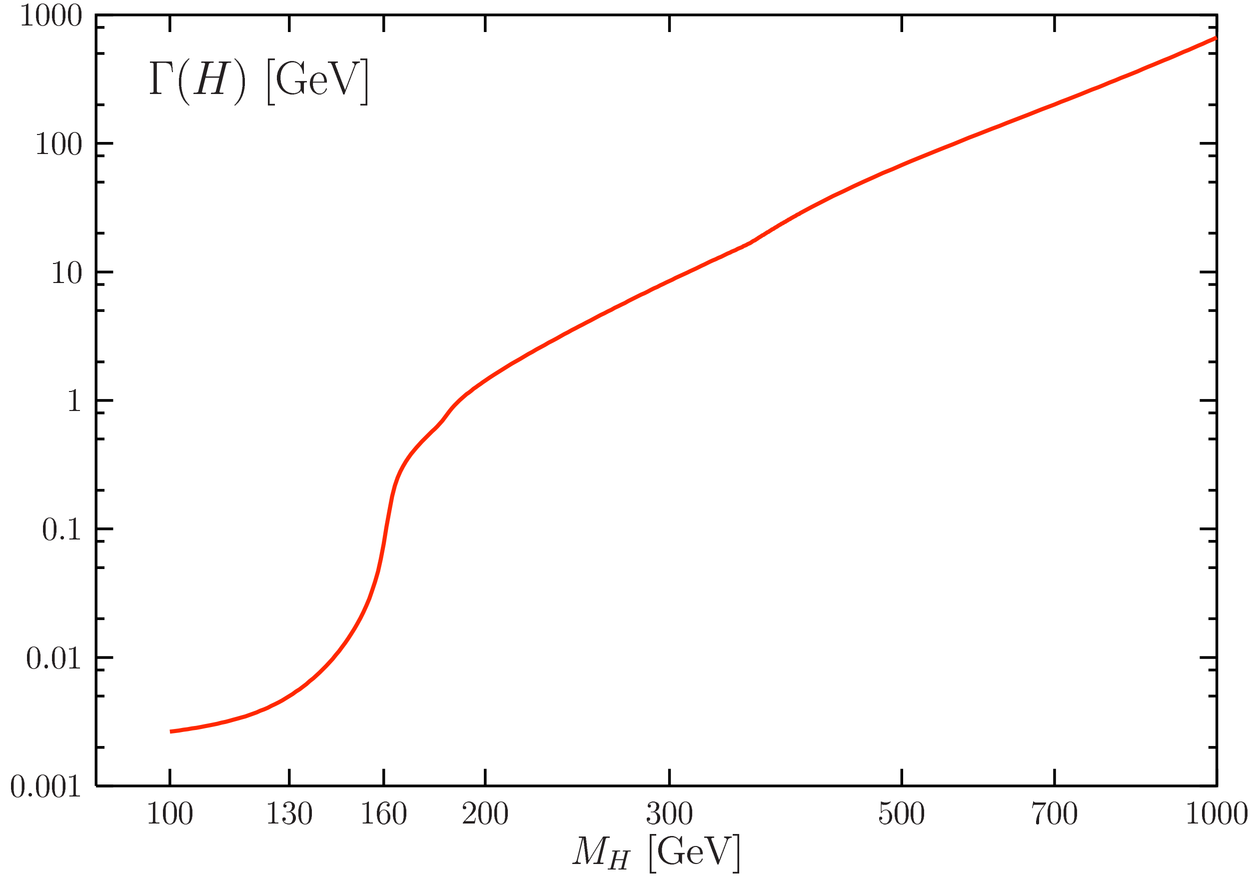
→ it is sensitive to new physics

SM Higgs decay



loop-induced

SM Higgs decay



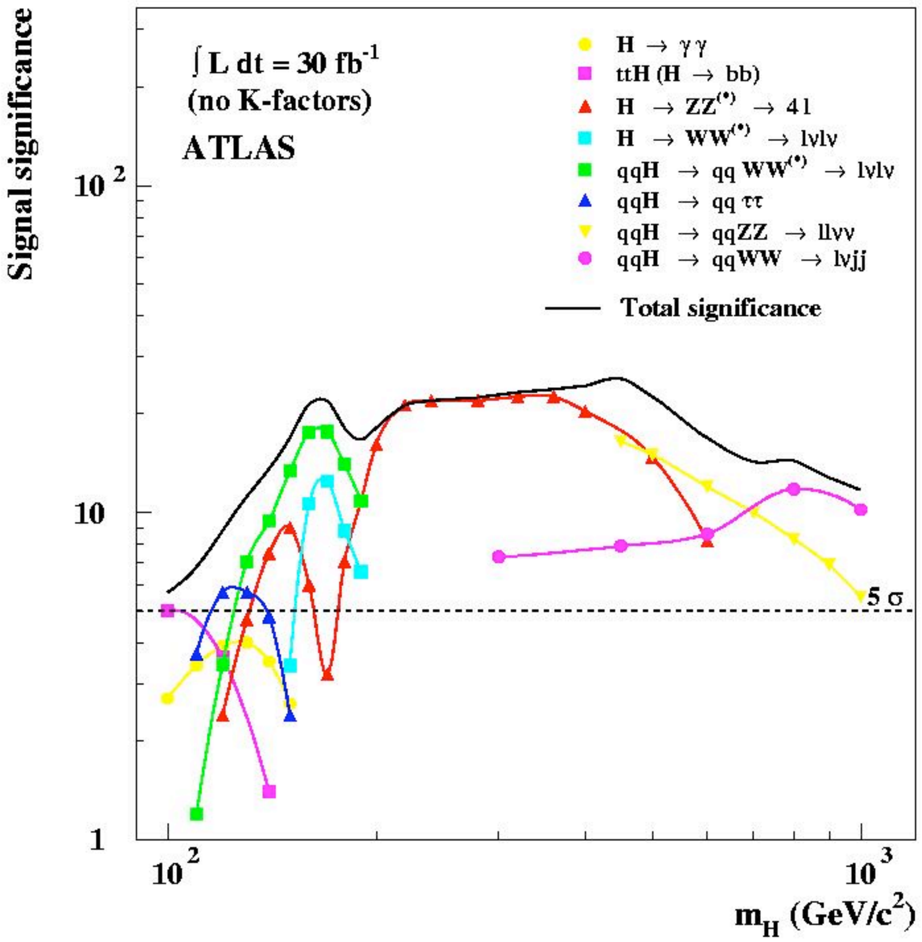
For $m_H < 160$ GeV, Higgs decay width is very small.

$$(\Gamma_Z = 2.4952 \text{ GeV}, \quad \Gamma_W = 2.141 \text{ GeV})$$

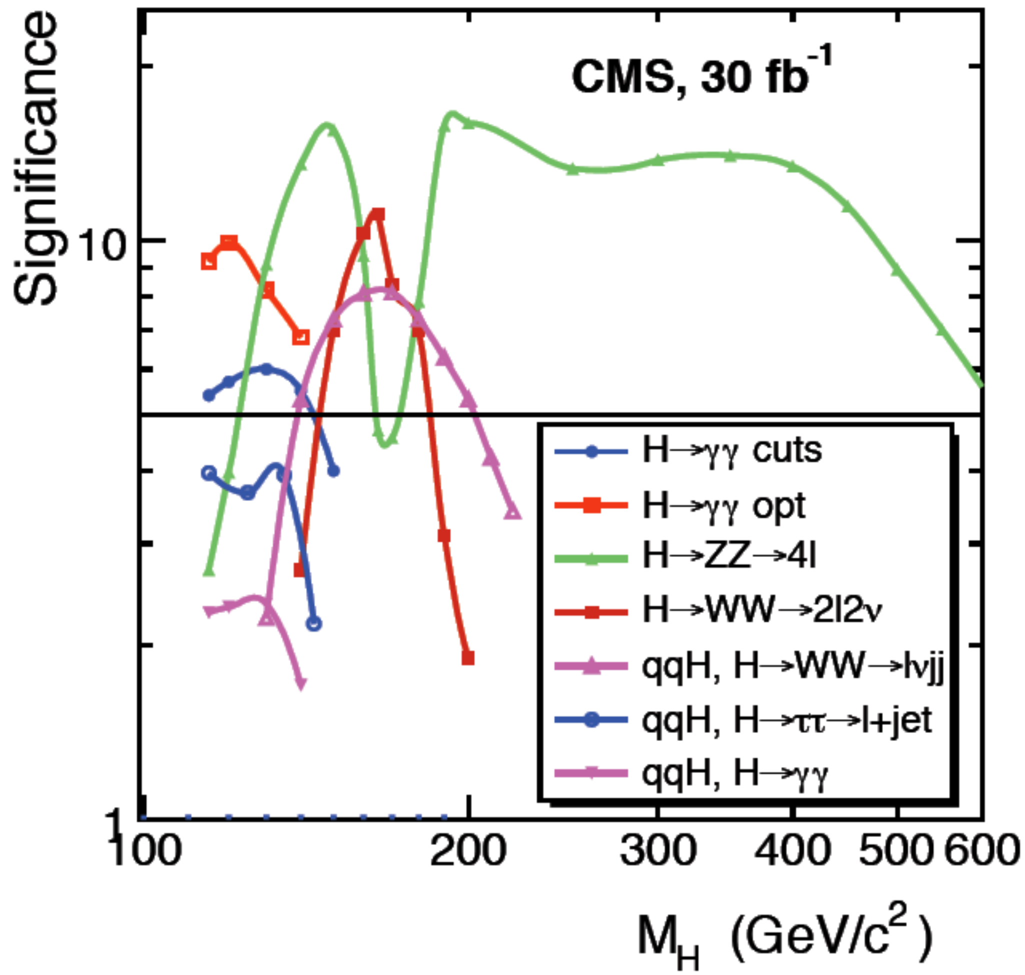
→ new physics can easily change the decay branching ratios

LHC experiments have a great potential to discover a SM Higgs boson in various channels.

2003, no k factors



2006, k factors

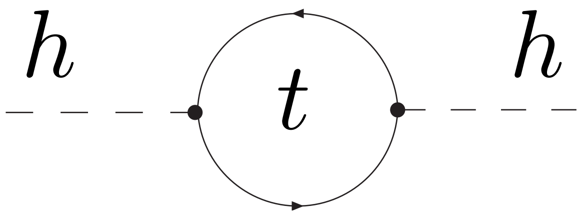


SM Higgsの発見は確実

Non Standard Model Higgs を考える理由

★ SM Higgs boson has a problem (Naturalness problem)

SM Higgs boson mass term receives large radiative corrections.

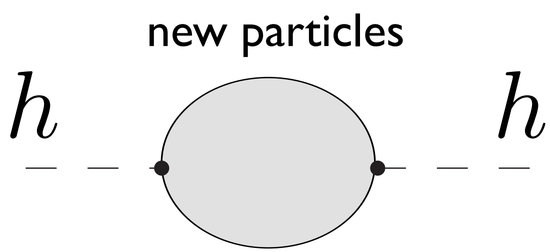


$$\delta M_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2$$

Why is electroweak scale so small?

There is no symmetry (mechanism) which guarantees the small Higgs mass in the SM.

➡ New Physics contribution to Higgs mass term may cancel the large corrections.

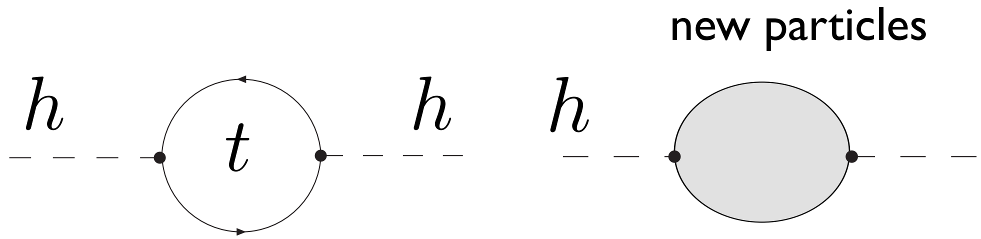


★supersymmetry (SUSY)

★Little Higgs etc....

Higgs boson has new interactions with new particles.

When we introduce such a new physics....



- Higgs sector may be modified. Higgs can mix with other state.

e.g. MSSM is a two Higgs doublet model

Interactions with SM particles can be modified

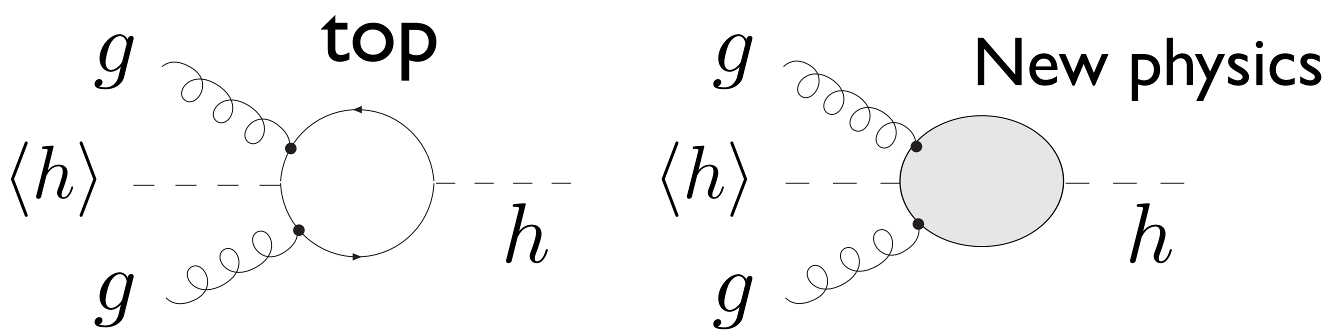
- Higgs has new interactions with new particles

Higgs may decay into new particles

$$\Gamma(h \to b\bar{b}) \ll \Gamma(h \to XX)$$

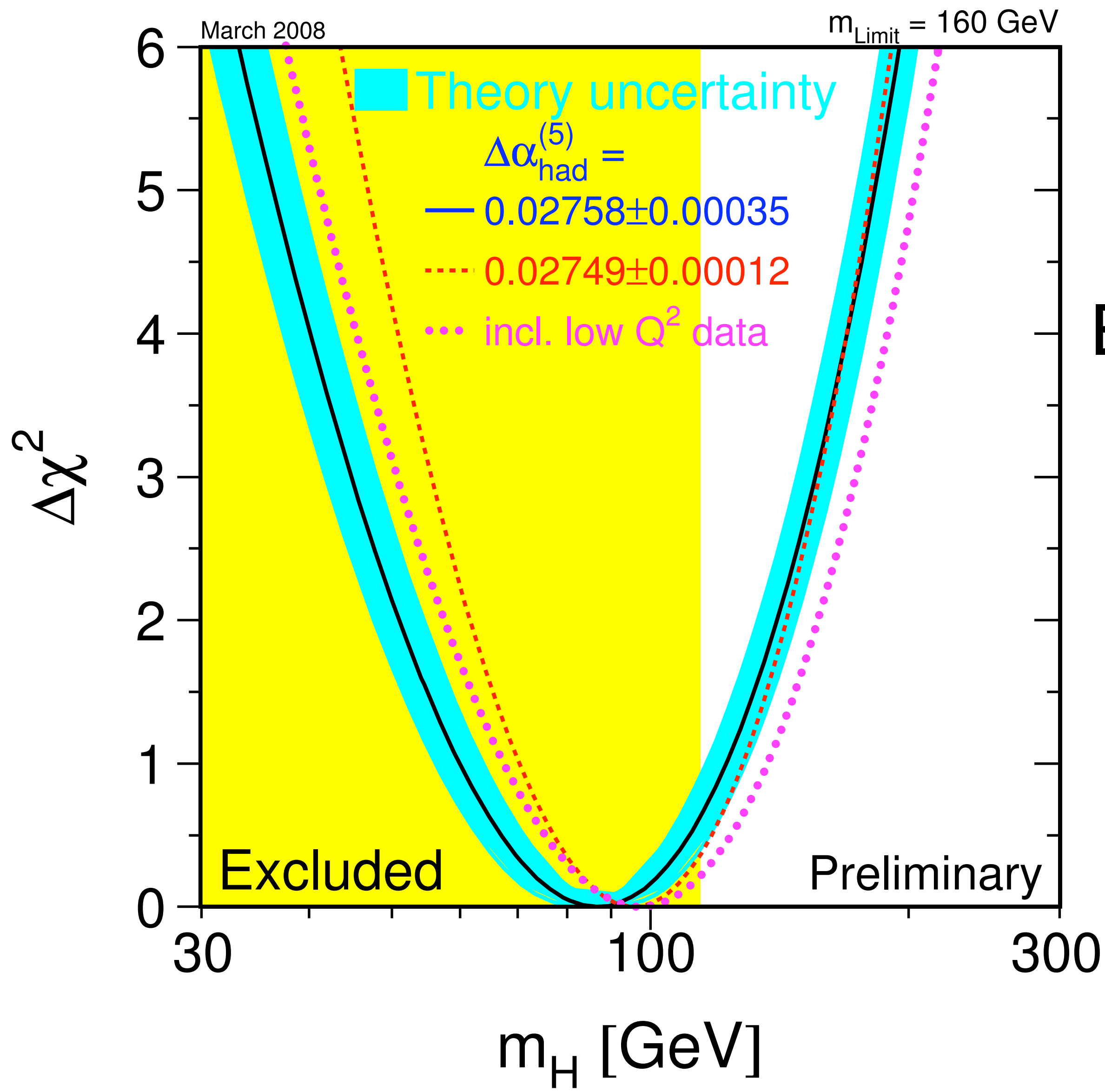
The decay branching ratios can be changed

gluon fusion (decay to photons) is modified



➡ Higgs phenomenology can be largely affected by the new physics

★current SM Higgs mass limits



LEP limit

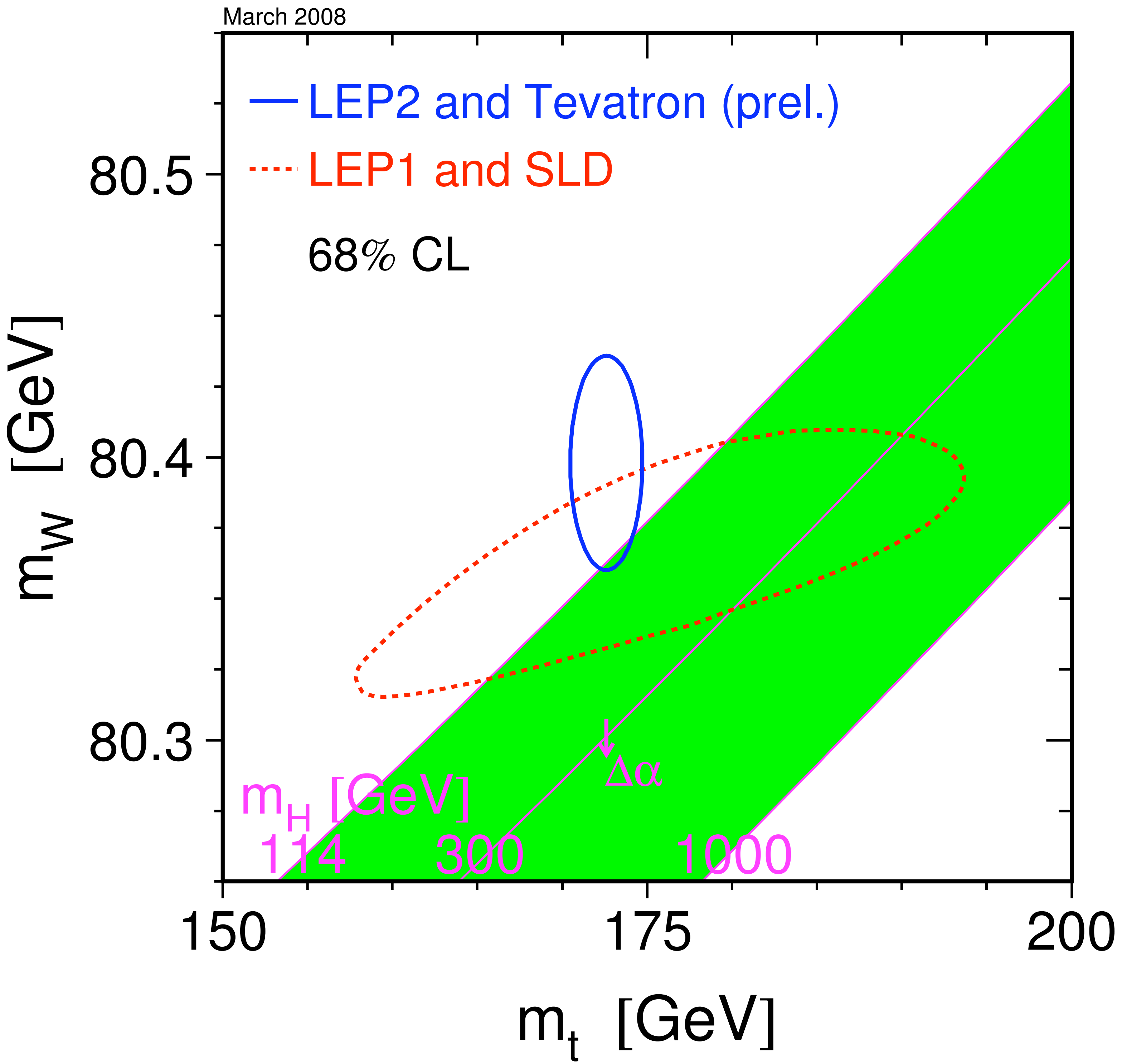
$$m_H > 114 \text{ GeV}$$

EW precision measurements

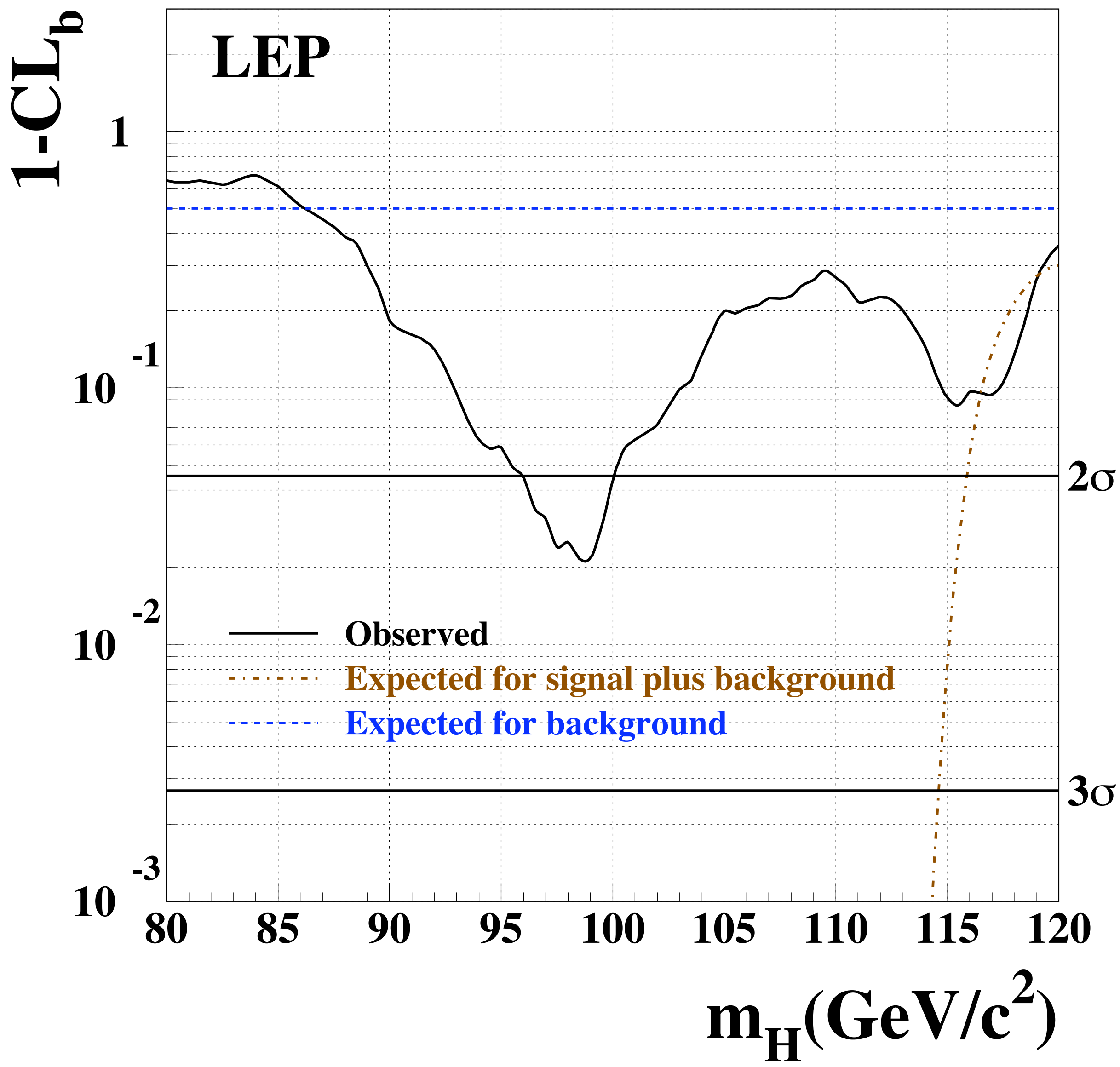
$$m_H = 87^{+36}_{-27} \text{ GeV}$$

$$m_H < 160 \text{ GeV } (95\ \% \text{ C.L.})$$

The EW measurements prefer a light Higgs (even lighter than the LEP limit).


March 2008
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

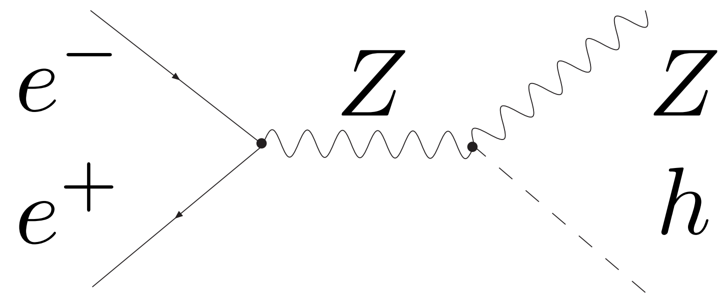
★Higgs-like events at around 98 GeV at LEP



SM Higgs can not explain this excess. This may be explained if

$$\sigma(Zh) \times \mathrm{BR}(h \to b\bar{b})$$

is about 10 % of the SM prediction.



For example, see
G. Kane et al, hep-ph/0407001
M. Drees hep-ph/0502075
S.-G. Kim et al, hep-ph/0609076

This result may be indicating the nonstandard model Higgs boson ?!.....

Higgs が見えなくなる可能性はあるのか？

- Higgs が他のスカラーとミックスする

dimension 2 operator $H^\dagger H$ is a gauge singlet

$$\mathcal{L} = -\mathcal{O} H^\dagger H$$

$\mathcal{O} = N^\dagger N$: singlet in NMSSM

$\mathcal{O} = R(g_{\rm ind})$:Ricci scalar of 4d metric in RS model

"Higgs-radion mixing"

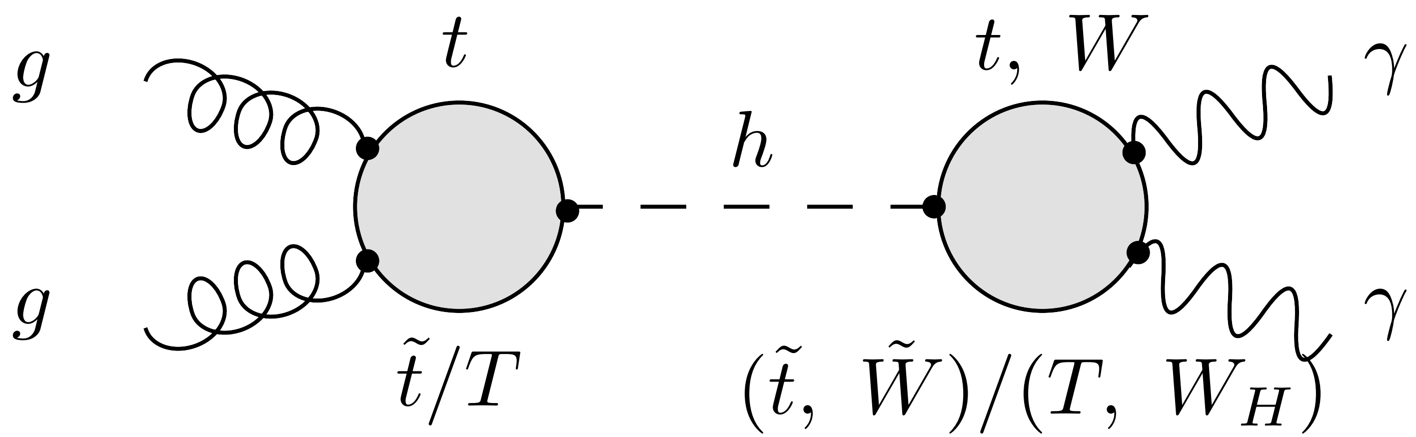
Higgs interactions with SM particles can be suppressed

- Higgs がSM particle以外の粒子にdecayする

$$\Gamma(h \to b\bar{b}) \ll \Gamma(h \to XX)$$

Higgs decay branching ratios to SM particles can be reduced

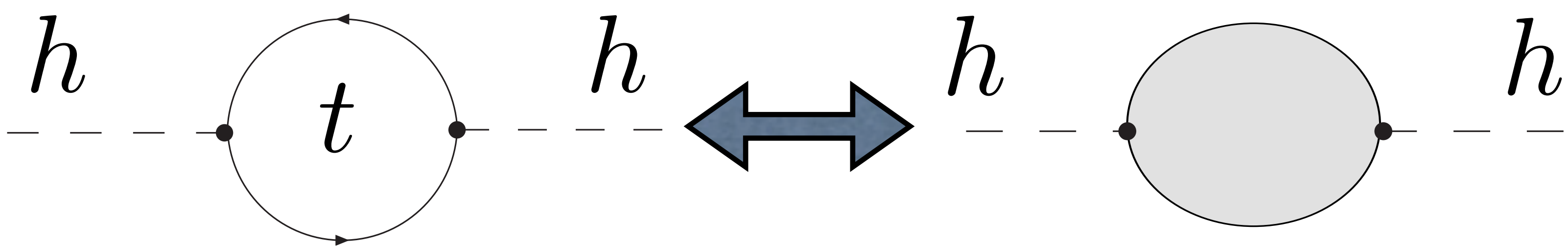
- gluon fusionやtwo photon decayがsuppress される



new physics (SUSY/Little Higgs)

Remember.....

new particles



cancellation!

- Higgs が他のスカラーとミックスする
- Higgs がSM particle以外の粒子にdecayする
- gluon fusionやtwo photon decayがsuppress される

SMで期待されるシグナルイベント数（$\sigma \times \mathrm{BR}$）

が大幅に小さくなるとHiggsが見えなく

（少なくとも見えづらく）なる可能性

例えば、シグナルの $\sigma \times \mathrm{BR}$ が1/3になったとすれば、発見に

必要なルミノシティーは単純には $3^2 = 9$ 倍必要になる

$$(30\ \mathrm{fb}^{-1} \to 30 \times 9 = 270\ \mathrm{fb}^{-1})$$

$$\mathrm{Significance} = \frac{S}{\sqrt{B}} = \frac{\sigma_{\mathrm{signal}}}{\sqrt{\sigma_{bkgd}}}\sqrt{\mathcal{L}}$$

S: number of signal event

B: number of background

L: integrated luminosity

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   by Dermisek, Gunion, and more...

3. Radion-Higgs mixing in Randall-Sundrum model

   by Guidice, Rattazzi, Wells,
   Hewett, Rizzo,
   Dominici, Grzadkowski, Gunion, Toharia, and more....

   Light Higgs scenario in MSSM

   by Belyaev et al, and more

Summary

Higgsが見えにくくなる可能性

1. Suppression of gluon fusion in Little Higgs models (and SUSY models)

by Chen, Tobe and Yuan

Little Higgs mechanism (collective symmetry breaking)

- Higgs boson is a pseudo Nambu-Goldstone boson which is light because of approximate global symmetries. Georgi and Kaplan
- Global symmetries are broken explicitly by two sets of interactions.

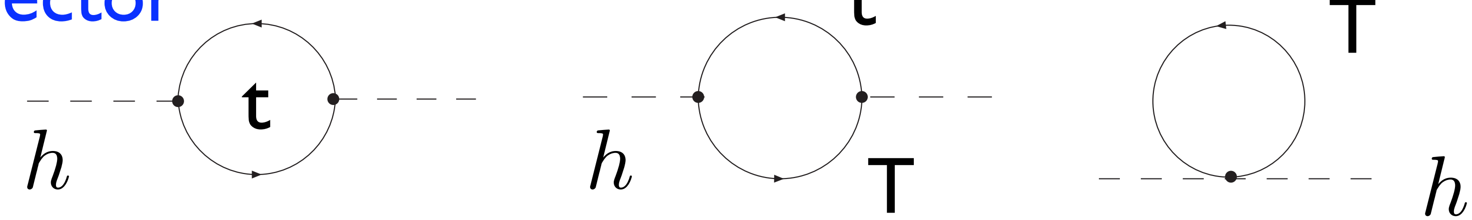
Arkani-Hamed, Cohen, Georgi

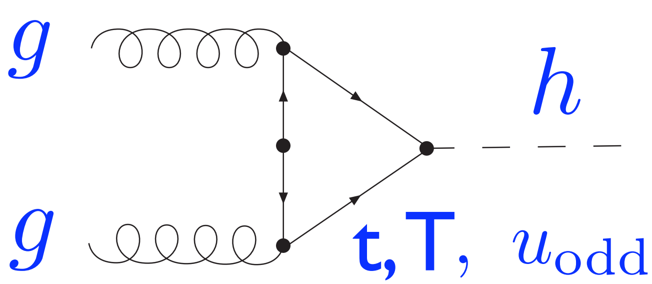
$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

$$\delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2$$

$$\sim O(100)\mathrm{GeV} \ \text{for} \ \Lambda \sim 10 \ \mathrm{TeV}$$

Top sector



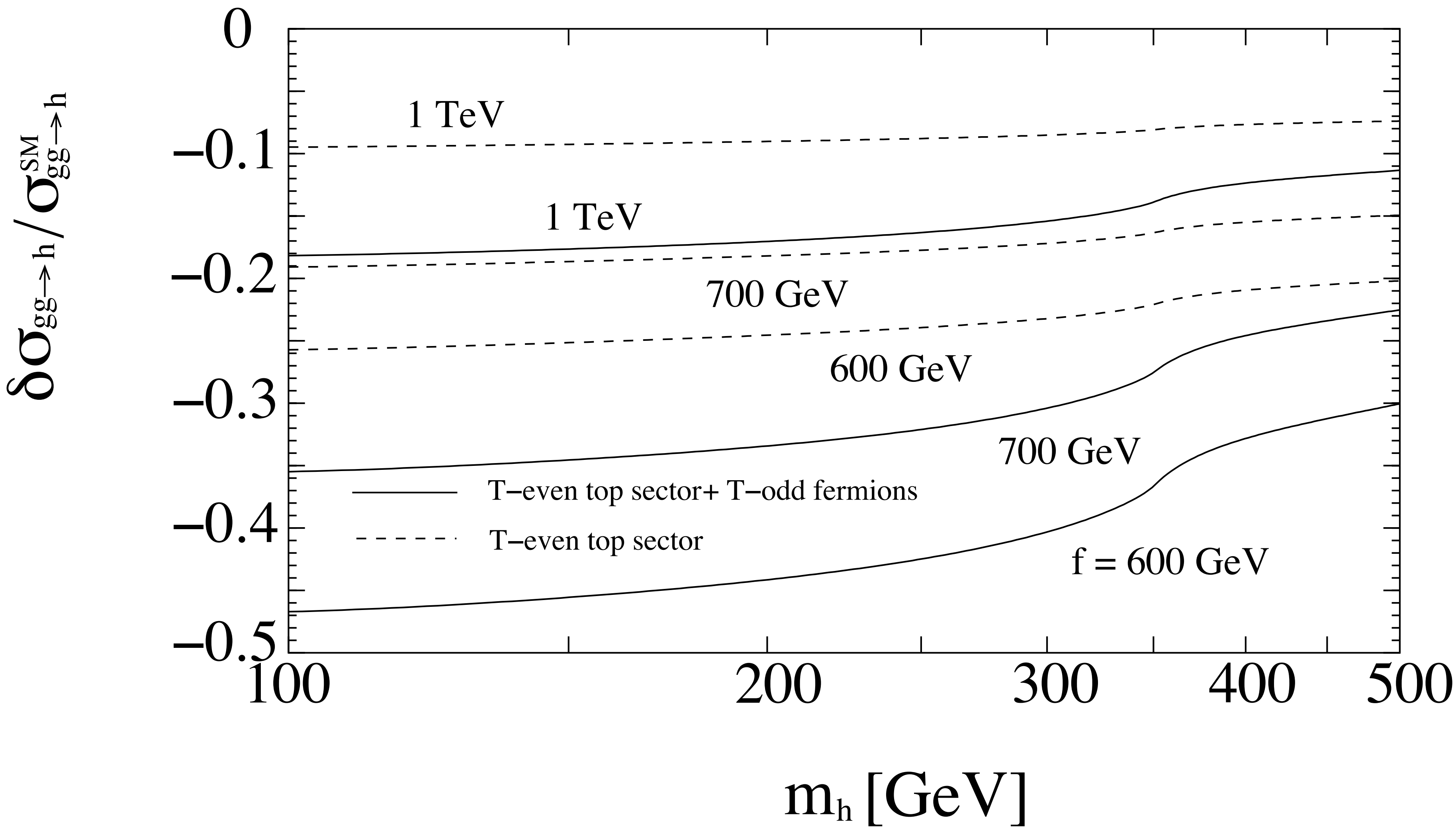


gluon fusion process is modified

Correction to Higgs production cross section via gluon fusion process

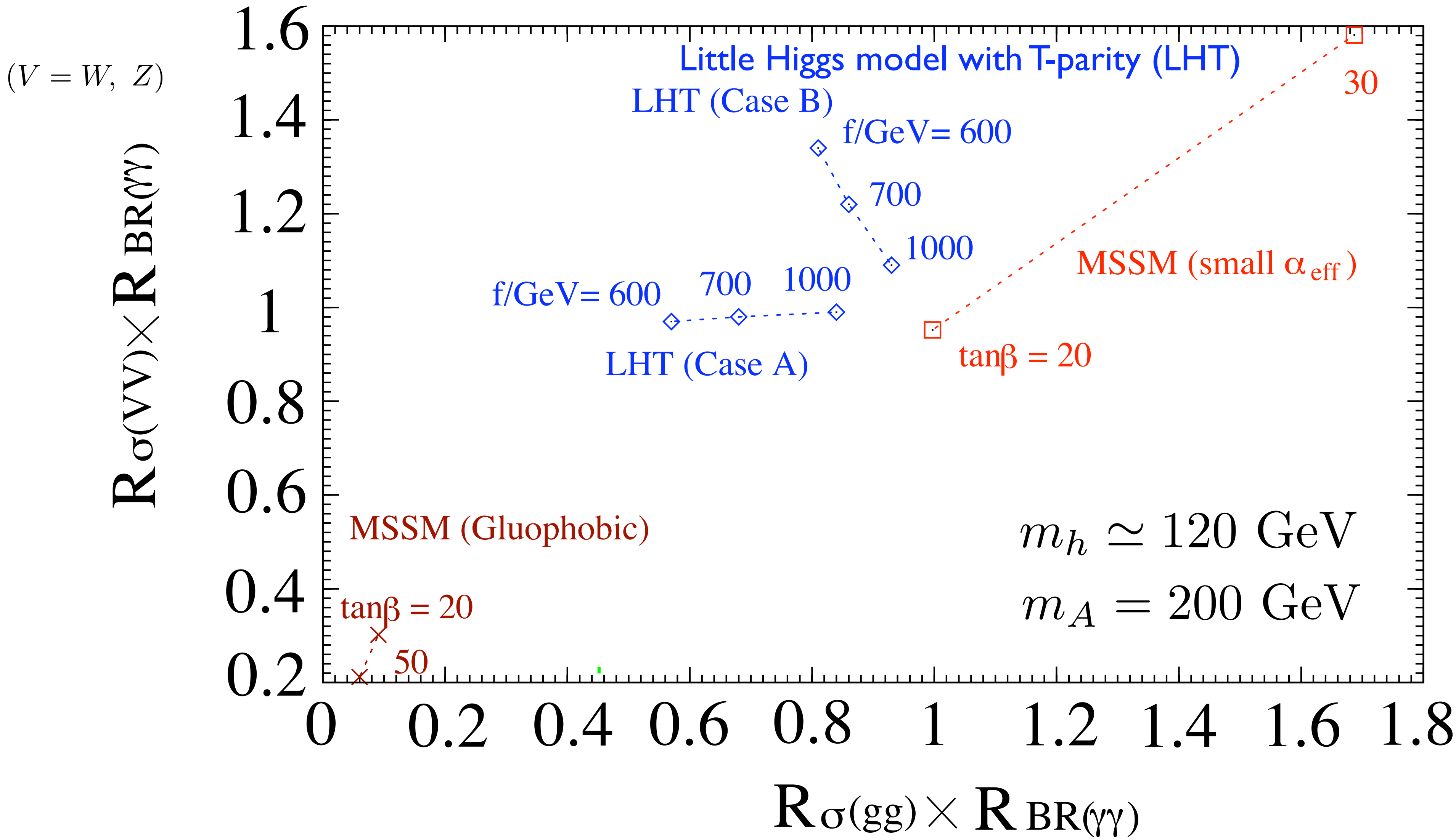
$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \quad (\text{where } \delta\sigma_{gg\to h} = \sigma^{\rm LH}_{gg\to h} - \sigma^{\rm SM}_{gg\to h})$$

Chen, Tobe, Yuan: hep-ph/0602211



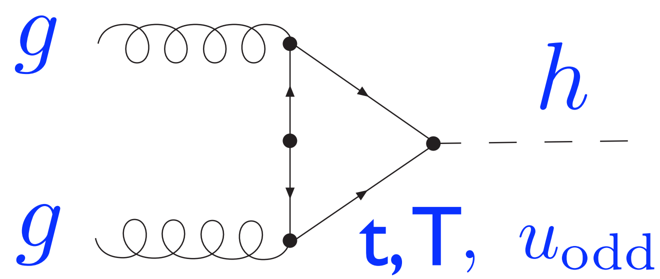
The production cross section can be significantly suppressed

For example: SUSY (benchmarks) vs. little Higgs model



R: nomalized by the SM prediction

Higgs discovery may need more luminosity, but....



When the new physics contribution is large, the new particle (T in Little Higgs case) should be within the reach at LHC.

Heavy T search at LHC

Matsumoto-san's talk(?)

2. Nonstandard Higgs boson decays in NMSSM

by Dermisek, Gunion

Little hierarchy problem in minimal supersymmetric model (MSSM)

LEP limit on SM Higgs mass $m_H > 114 \text{ GeV}$

MSSM Higgs mass prediction

$$m_H^2 \simeq M_Z^2 \cos^2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \left\{ \log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2} \right) \right\}$$

To satisfy $m_H > 114 \text{ GeV}$

typically $m_{\tilde{t}} > 1 \text{ TeV}$ for $A_t / m_{\tilde{t}} \ll 1$

On the other hand, EW breaking condition requires

$$\frac{M_Z^2}{2} \simeq -\mu^2 - m_{H_u}^2 \sim m_{\tilde{t}}^2 + \cdots$$

assuming some universality at GUT scale

need some tuning for the EW scale

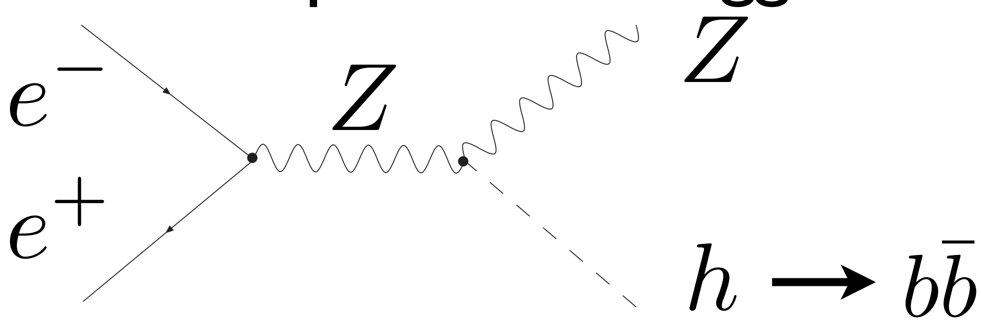
One of the solutions may be ....

If the LEP Higgs limit is $m_H \sim 100 \text{ GeV}$

$$m_{\tilde{t}} > 300 \text{ GeV } (110 \text{ GeV}) \text{ for } \tan\beta = 5, \; A_t/m_{\tilde{t}} = 0 \; (\sqrt{3})$$

no serious fine-tuning

- $m_H \sim 100 \text{ GeV}$ is totally consistent with EW precision measurements
- it is possible to explain "LEP Higgs excess" at 98 GeV



all Higgs interactions to the SM particles are SM-like, but $\mathrm{BR}(h \to b\bar{b}) \sim 0.1$

This is possible if the Higgs has other decay mode.

$h \to aa$ in Next to Minimal Supersymmetric Model (NMSSM, that is, MSSM + singlet)

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

$$(h:\ \text{SM like Higgs},\ a:\ \text{CP}-\text{odd Higgs coming mostly from the singlet})$$

Since hbb coupling is so small,
$h \to aa$ can be easily a dominant decay mode.

If dominant decay mode of a is $a \to b\bar{b}$,
LEP limit $m_H > 110\ \text{GeV}$

When the mass of a is below $b\bar{b}$ threshold,
the dominant decay mode will be $\tau^+\tau^-$ or 2 jets

LEP limit $m_H > 86\ \text{GeV}$

m_{h_1}/m_{a_1} (GeV)	Branching Ratios $h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau\bar{\tau}$	$n_{\rm obs}/n_{\rm exp}$ units of 1σ	$s95$	N_{SD}^{LHC}
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2

Dermisek, Gunion
PRD73, 111701 (2006)

TABLE I: Some properties of the h_1 and a_1 for the eight allowed points with $F < 10$ and $m_{a_1} < 2m_b$ from our $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV NMSSM scan. The $n_{\rm obs}$, $n_{\rm exp}$ and $s95$ values are obtained after full processing of all Zh final states using the preliminary LHWG analysis code (thanks to P. Bechtle). See text for details. N_{SD}^{LHC} is the statistical significance of the best "standard" LHC Higgs detection channel for integrated luminosity of $L = 300$ fb^{-1}.

SM particlesへのBRが抑制されるので、"Standard" LHC Higgs detection channelのStatistical significanceが大きく減ってしまう。

Search for $h \to aa$ at LHC

$h \to aa \to b\bar{b}b\bar{b}$ case

Cheung, Song, Yan (2007)
Carena, Han, Huang, Wagner (2007)

$Wh \to 4jl\nu$ requiring three or four b-tagged jets

For a 120 GeV Higgs,

5σ discovery at the LHC requires about $30\ \mathrm{fb}^{-1}$

(b-tagging efficiencies of 50 % at $p_T \sim 15$ GeV)

If this efficiency only hold for $p_T > 30$ GeV

need $80\ \mathrm{fb}^{-1}$ for discovery

$h \to aa \to \tau^+\tau^-\tau^+\tau^-$ case

$WW \to h \to 4\tau$

"Studies of this mode have begun"

Chang, Dermisek, Gunion, Weiner (2008)

3. Radion-Higgs mixing in Randall-Sundrum model

In the RS model, the background metric is defined by

$$ds^2 = e^{-2kr_c|y|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 dy^2$$

This metric suggests two types of massless excitations described by

$$\eta_{\mu\nu} \longrightarrow g_{\mu\nu}(x) \quad \text{graviton}$$

$$r_c \longrightarrow T(x) \quad \text{radion}$$

$$ds^2 = e^{-2k|y|T(x)}g_{\mu\nu}(x)dx^\mu dx^\nu - T^2(x)dy^2$$

It is convenient to express the radion field in terms of a canonically normalized field φ

$$\varphi \equiv \Lambda_\varphi e^{-k\pi(T-r_c)}, \ \Lambda_\varphi \equiv \langle\varphi\rangle = \sqrt{\frac{24M^3}{k}}e^{-k\pi r_c}$$

Goldberger and Wise

mechanism to stabilize T such that $k\pi r_c \sim 35$
which explains the hierarchy between weak and Planck scales

One consequence of the GW mechanism is that the radion should be somewhat lighter than the Kaluza-Klein modes of any bulk field.

The radion can mix with Higgs via

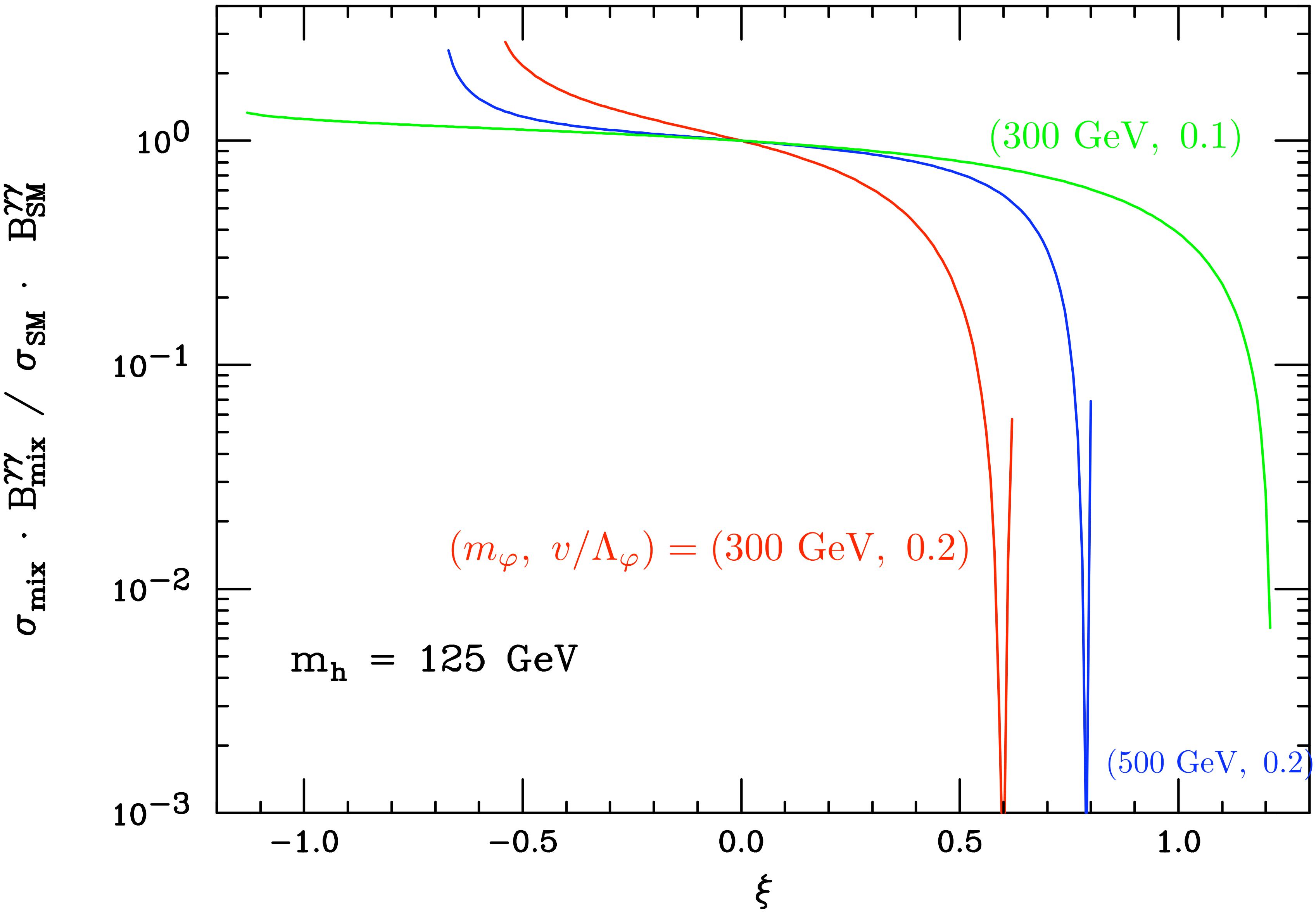
$$S = -\xi \int d^4x \sqrt{-g_{\rm ind}} R(g_{\rm ind}) H^\dagger H$$

R: Ricci scalar of the induced 4-d metric on the SM brane

This radion-Higgs mixing can change the Higgs phenomenology at the LHC.

$pp \to h \to \gamma\gamma$ via gluon fusion

Hewett and Rizzo
hep-ph/0202155



gluon fusion can be small due to the top-loop and trace anomaly contributions.

Higgs discovery in this channel will be difficult.

Higgs discovery vs. Radion discovery

h: "standard" Higgs search channels

$\varphi \to ZZ^{(*)} \to 4l$

CMS NOTE-2005/007

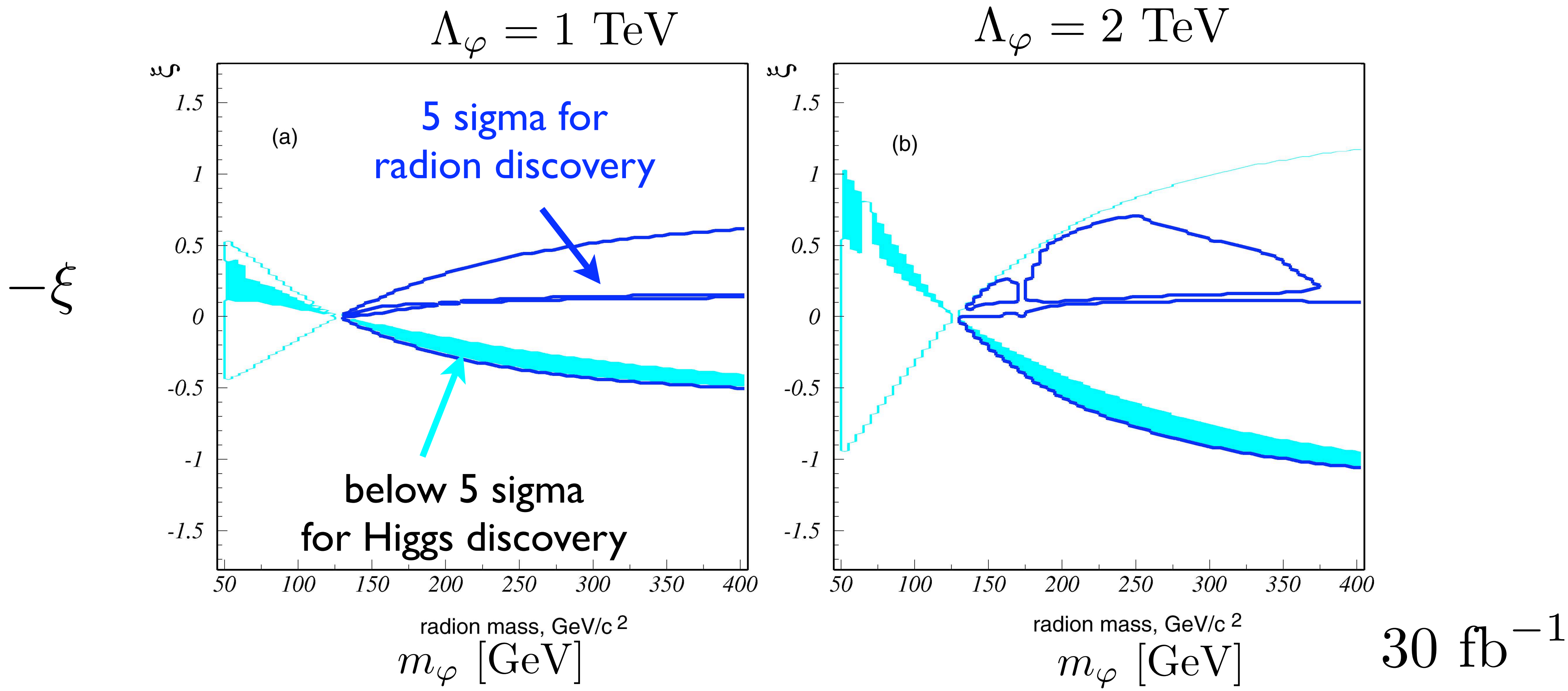


Figure 15: The light grey (cyan) regions show the part of the (M_ϕ, ξ) parameter space where the significance of the Higgs boson discovery with $h \to \gamma\gamma$, $t\bar{t}h$ $(h \to b\bar{b})$, $h \to ZZ^* \to 4\ell$, $h \to WW^* \to 2\ell$, qqh $(h \to \tau\tau)$ and Wh $(h \to \gamma\gamma)$ channels drops below 5σ. The regions inside thick (blue) curves are the ones where the significance of the $\phi \to ZZ^{(*)} \to 4\ell$ signal exceeds 5σ. The outermost contours define the theoretically allowed region. Results are presentd for m_h=125 GeV/c^2, Λ_ϕ = 1 TeV (a) and 2 TeV (b) and for 30 fb^{-1}.

$$\varphi \to hh \to \gamma\gamma + b\bar{b}$$

CMS NOTE-2005/007

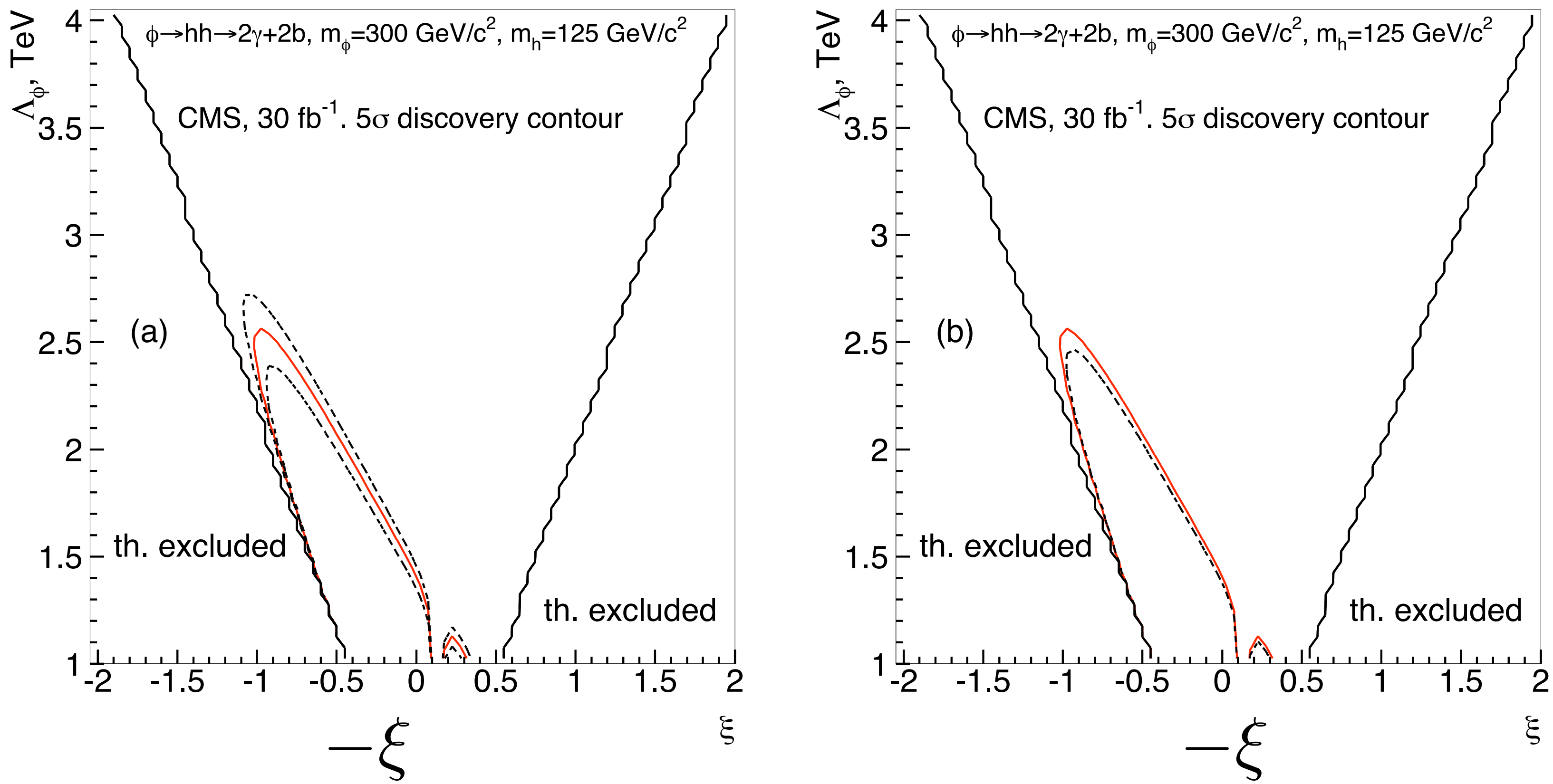
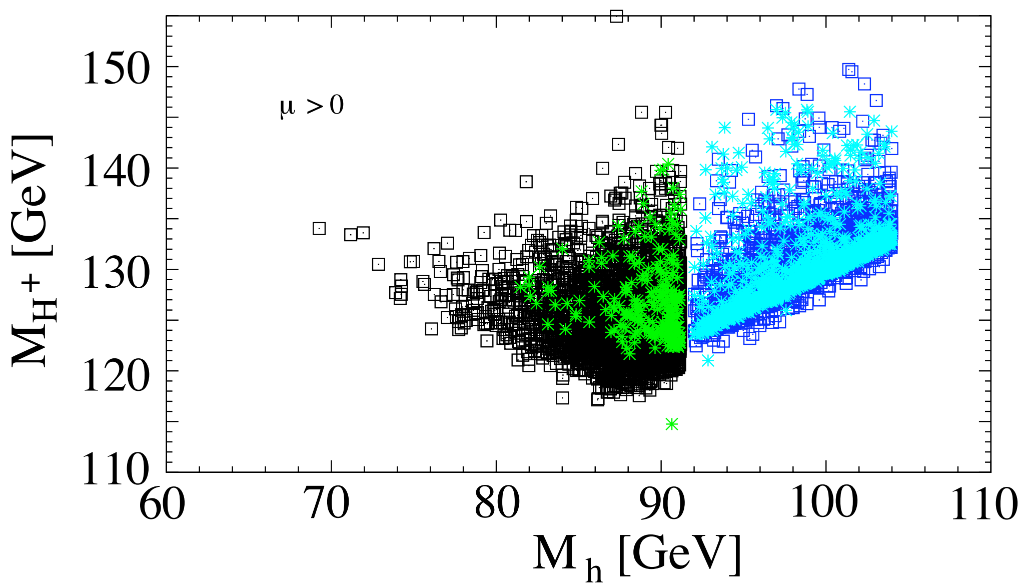


Figure 14: The 5σ discovery contours for $\phi \to \mathrm{hh} \to \gamma\gamma + \mathrm{b\bar{b}}$ channel (m_ϕ=300 GeV/c^2, $\mathrm{m_h}$=125 GeV/c^2) with 30 fb^{-1}. In (a) the solid contour shows the discovery region for the renormalization and factorization scales $\mu_\mathrm{r} = \mu_\mathrm{f} = \mathrm{M_Z}$. The dashed contours refer to $\mu_\mathrm{r} = \mu_\mathrm{f} = 0.5\ \mathrm{M_Z}$ and $2\ \mathrm{M_Z}$. In (b) the solid (dashed) contours show the discovery region without (with) the effects of the systematic uncertainties for $\mu_\mathrm{r} = \mu_\mathrm{f} = \mathrm{M_Z}$.

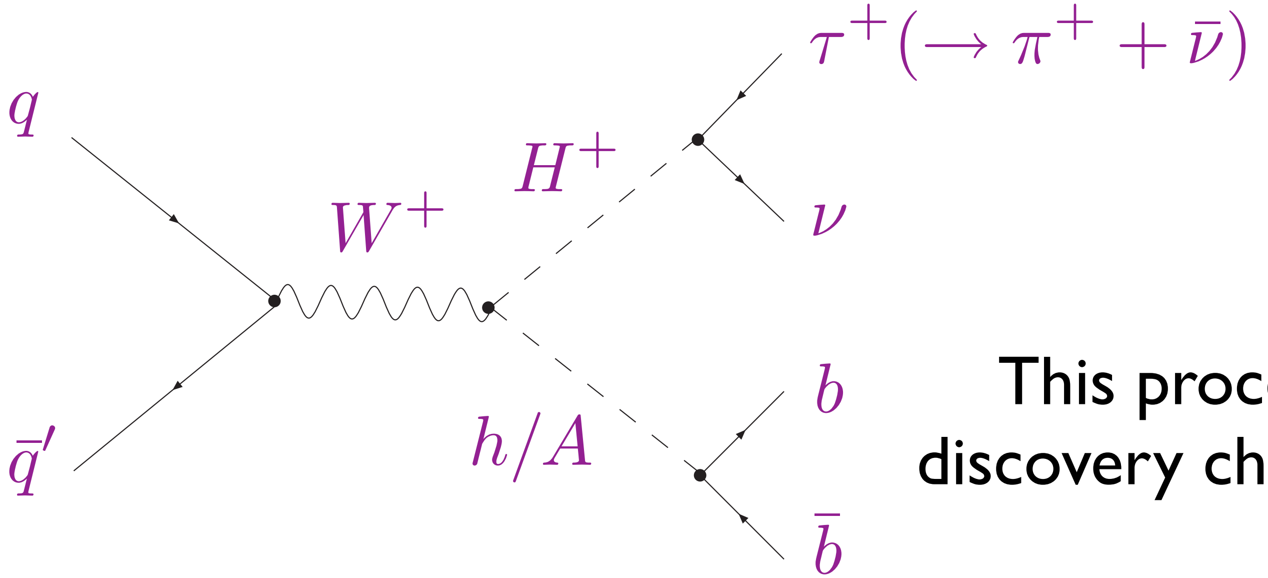
Higgs can be discoverd in $\varphi \to hh$ channel

Possibility of light MSSM Higgs bosons



Belyaev, Cao, Nomura, Tobe, Yuan
PRL 100, 061801 (2008)

Mainly due to the reduced ZZh coupling, light Higgs boson (~70-110 GeV) is still allowed in MSSM.



This process will be important discovery channel for the light Higgs

Summary

- SM Higgs boson will be discovered at LHC if it exists.
- Non-SM Higgs can be realized in many well-motivated models

★ Gluon-fusion (and/or diphoton decay) of Higgs can be affected by the mechanism to solve the hierarchy problem

Little Higgs models and some SUSY models

★ non-SM Higgs decay can change the Higgs branching ratios to SM particles

$h \to aa$ in NMSSM

★ Higgs mixing to other scalar can reduce the interactions to SM particles

Higgs-radion mixing

Light MSSM Higgs scenario

reduction of Higgs signal rate

Non-standard Higgs discovery channels may need to be studied to discover Higgs boson!

backup slides

Collective symmetry breaking

Gauge symmetries $[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2$

are embedded in global SU(5)

$$Q^a_{SU(2)_1} = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_1 = \frac{1}{10}\begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix}$$

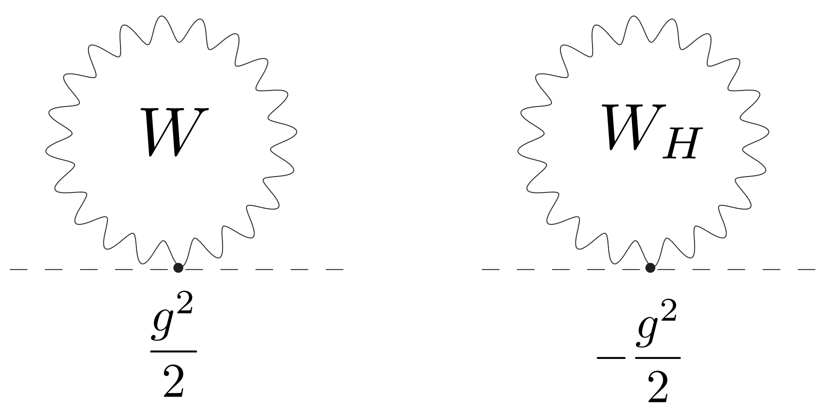
➡preserve SU(3)

$$Q^a_{SU(2)_2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix} \qquad Y_2 = \frac{1}{10}\begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

➡preserve SU(3)

Either SU(3) is enough to keep Higgs massless.

Sum of all gauge interactions break both SU(3)s and generate the Higgs mass.



Λ^2 corrections are canceled.

★ Top sector

The largest quadratically divergent one-loop contribution to the Higgs mass parameter in the SM comes from the top quark loop. Thus the top sector has to be modified to cancel the large divergence.

Introducing a pair of weak-singlet Weyl fermions U_L and U_R and making the SU(3) triplet from the doublet $q_L = (u_L,\ d_L)^T$ and the singlet U_L : $Q_L = \begin{pmatrix} -\sigma_2 q_L \\ U_L \end{pmatrix}$

the Top Yukawa sector is given by

$$\mathcal{L} \quad = \quad -\frac{\lambda_1}{2} f \epsilon^{ijk} \epsilon^{xy} \bar{Q}_{Li} \Sigma_{jx} \Sigma_{ky} u_R - \lambda_2 f \bar{U}_L U_R + \text{h.c.}$$

collective symmetry breaking in the top sector

$$\mathcal{L} \quad = \quad -\frac{\lambda_1}{2} f \epsilon^{ijk} \epsilon^{xy} \bar{Q}_{Li} \Sigma_{jx} \Sigma_{ky} u_R - \lambda_2 f \bar{U}_L U_R + \text{h.c.}$$

If λ_1 is zero,

the Higgs does not couple to the top sector, so that there is no corrections to the Higgs mass parameter from the top sector.

If λ_2 is zero,

the global SU(3) is unbroken in the top Yukawa sector, so the Higgs is an NGB.

Any contributions to the Higgs mass have to involve both λ_1 and λ_2 . The one loop contributions are at most logarithmically divergent.

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 350 \text{ GeV}, \quad \mu = 300 \text{ GeV}, \quad M_2 = 300 \text{ GeV},$$
$$X_t^{\rm OS} = -750 \text{ GeV (FD calculation)}, \quad X_t^{\overline{\rm MS}} = -770 \text{ GeV (RG calculation)}$$
$$A_b = A_t, \quad m_{\tilde{g}} = 500 \text{ GeV} \ . \tag{5}$$

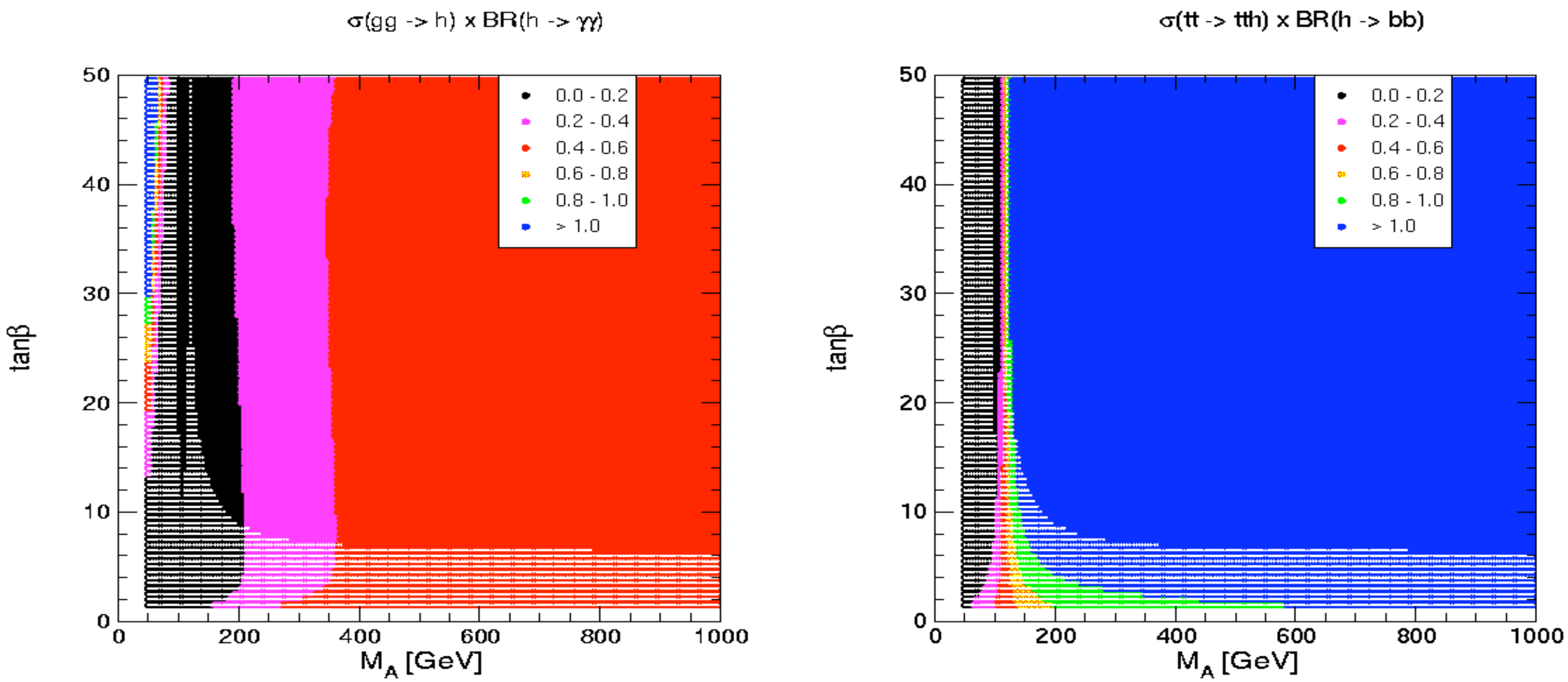
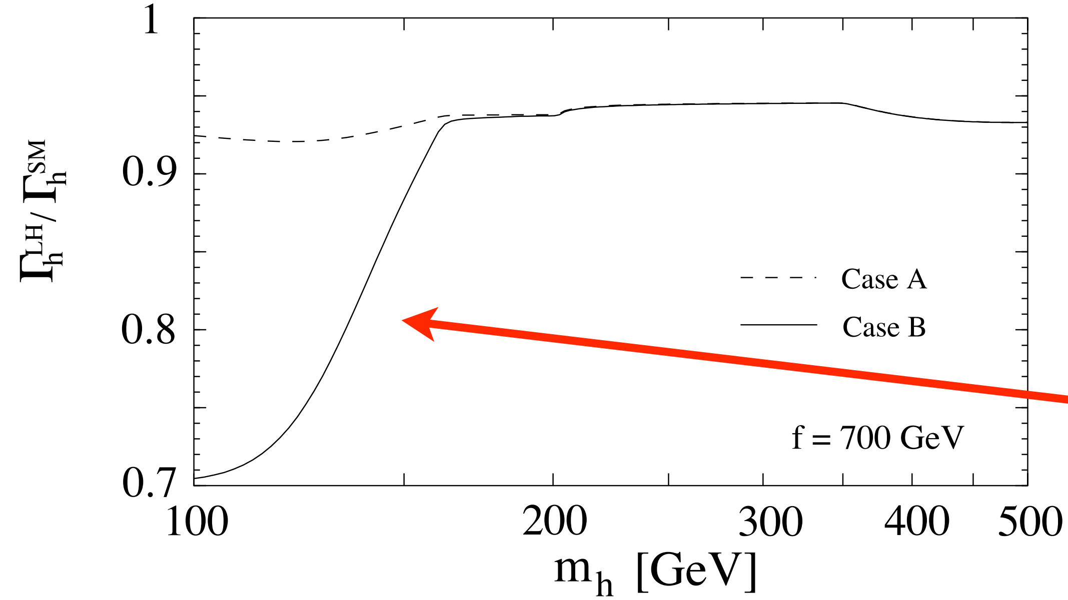


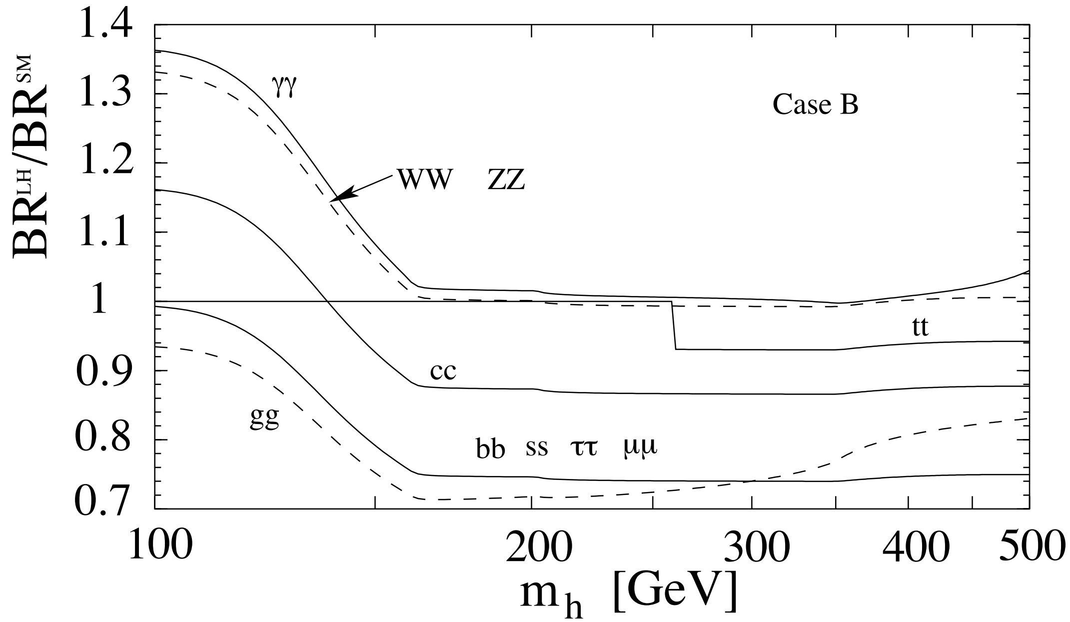
Figure 3: $[\sigma \times \mathrm{BR}]_{\rm MSSM}/[\sigma \times \mathrm{BR}]_{\rm SM}$ is shown for the channels $gg \to h \to \gamma\gamma$ (left plot) and $t\bar{t} \to t\bar{t}h \to t\bar{t}b\bar{b}$ (right plot) in the $M_A - \tan\beta$-plane for the gluophobic Higgs scenario. The white-dotted area is excluded by LEP Higgs searches.

Higgs total decay width normalized by the SM value



$b\bar{b},\ \tau^+\tau^-$
decay modes
are dominant.

Higgs decay branching ratios, normalized by the SM values



In Case B, because of the largely reduced total decay width in small Higgs mass region, some of the Higgs boson decay branching ratios are increased.

$$R_{\sigma(X)} = \frac{\sigma^{\mathrm{LH}}(X)}{\sigma^{\mathrm{SM}}(X)} \qquad R_{\mathrm{BR}(Y)} = \frac{\mathrm{BR}^{\mathrm{LH}}(Y)}{\mathrm{BR}^{\mathrm{SM}}(Y)}$$

$$R_{\sigma(X)} \times R_{\mathrm{BR}(Y)} \quad \text{for } f = (600,\ 700,\ 1000)\ \mathrm{GeV}$$

$m_h = 120$ GeV		$R_{\mathrm{BR}(\gamma\gamma)}$	$R_{\mathrm{BR}(\tau\tau)}$	$R_{\mathrm{BR}(b\bar{b})}$	$R_{\mathrm{BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	0.57, 0.68, 0.84	0.56, 0.67, 0.83	–	0.55, 0.66, 0.83
	(Case B)	0.81, 0.86, 0.93	0.51, 0.63, 0.81	–	0.78, 0.84, 0.92
$R_{\sigma(VV)}$	(Case A)	0.97, 0.98, 0.99	0.95, 0.96, 0.98	–	0.94, 0.96, 0.98
	(Case B)	1.34, 1.22, 1.09	0.84, 0.89, 0.95	–	1.30, 1.19, 1.08
$R_{\sigma(t\bar{t}h)}$	(Case A)	–	0.87, 0.90, 0.95	0.87, 0.90, 0.95	–
	(Case B)	–	0.77, 0.83, 0.92	0.77, 0.83, 0.92	–
$R_{\sigma(Vh)}$	(Case A)	0.97, 0.98, 0.99	–	0.95, 0.96, 0.98	–
	(Case B)	1.34, 1.22, 1.09	–	0.84, 0.89, 0.95	–
$m_h = 200$ GeV		$R_{\mathrm{BR}(\gamma\gamma)}$	$R_{\mathrm{BR}(\tau\tau)}$	$R_{\mathrm{BR}(b\bar{b})}$	$R_{\mathrm{BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	–	–	–	0.55, 0.67, 0.83
	(Case B)	–	–	–	0.56, 0.67, 0.83
$R_{\sigma(VV)}$	(Case A)	–	–	–	0.90, 0.94, 0.97
	(Case B)	–	–	–	0.90, 0.94, 0.97

- Higgs production via gluon fusion is suppressed.
- $\gamma\gamma,\ VV$ decay modes via weak boson fusion can be enhanced in small Higgs mass region in Case B.

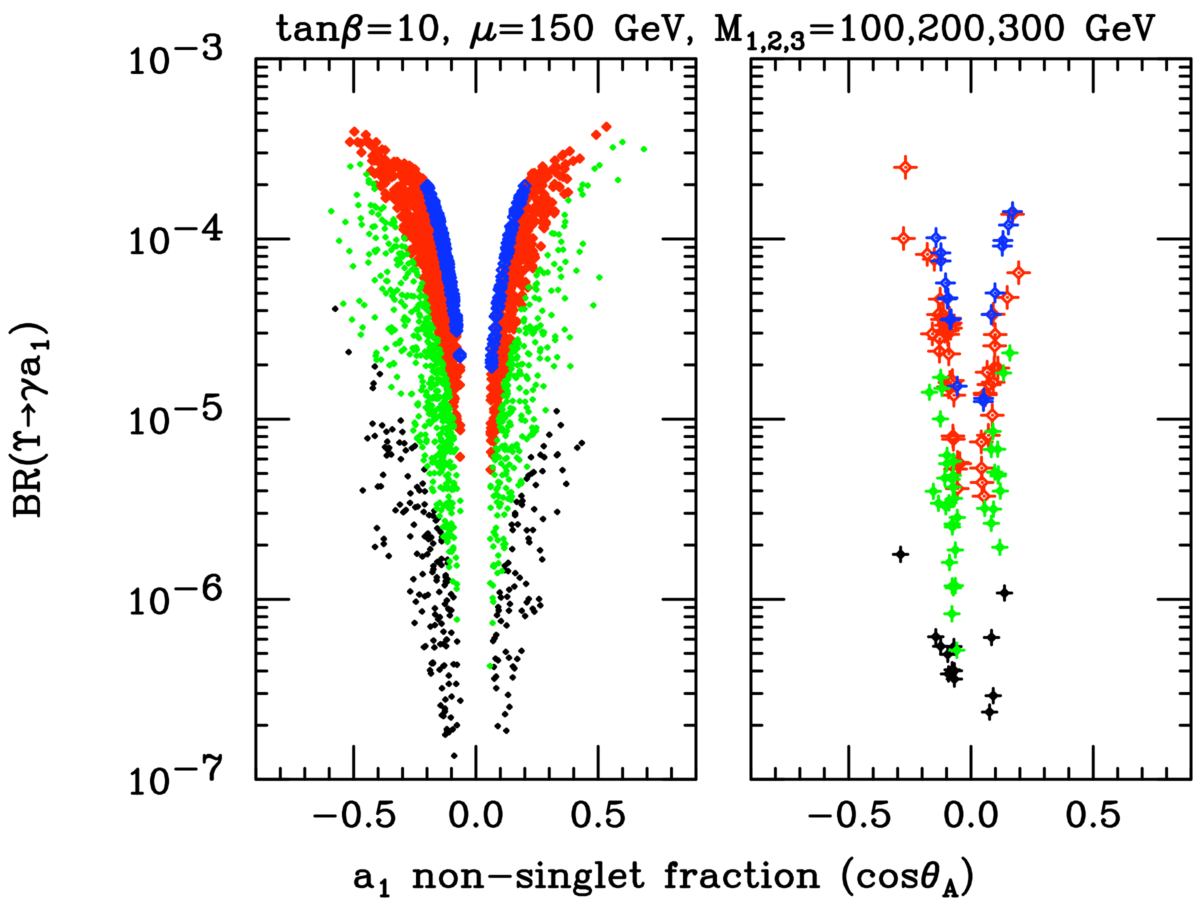


FIG. 1: $\mathrm{Br}(\Upsilon \to \gamma a_1)$ for NMSSM scenarios with various ranges for m_{a_1}: dark grey (blue) = $m_{a_1} < 2m_\tau$; medium grey (red) = $2m_\tau < m_{a_1} < 7.5$ GeV; light grey (green) = 7.5 GeV $< m_{a_1} <$ 8.8 GeV; and black = 8.8 GeV $< m_{a_1} <$ 9.2 GeV. The plots are for $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. The left plot comes from the A_λ, A_κ scan described in the text, holding $\mu_{\rm eff}(m_Z) = 150$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_{a_1} <$ 9.2 GeV found in a general scan over all NMSSM parameters holding $\tan\beta$ and $M_{1,2,3}$ fixed as stated.

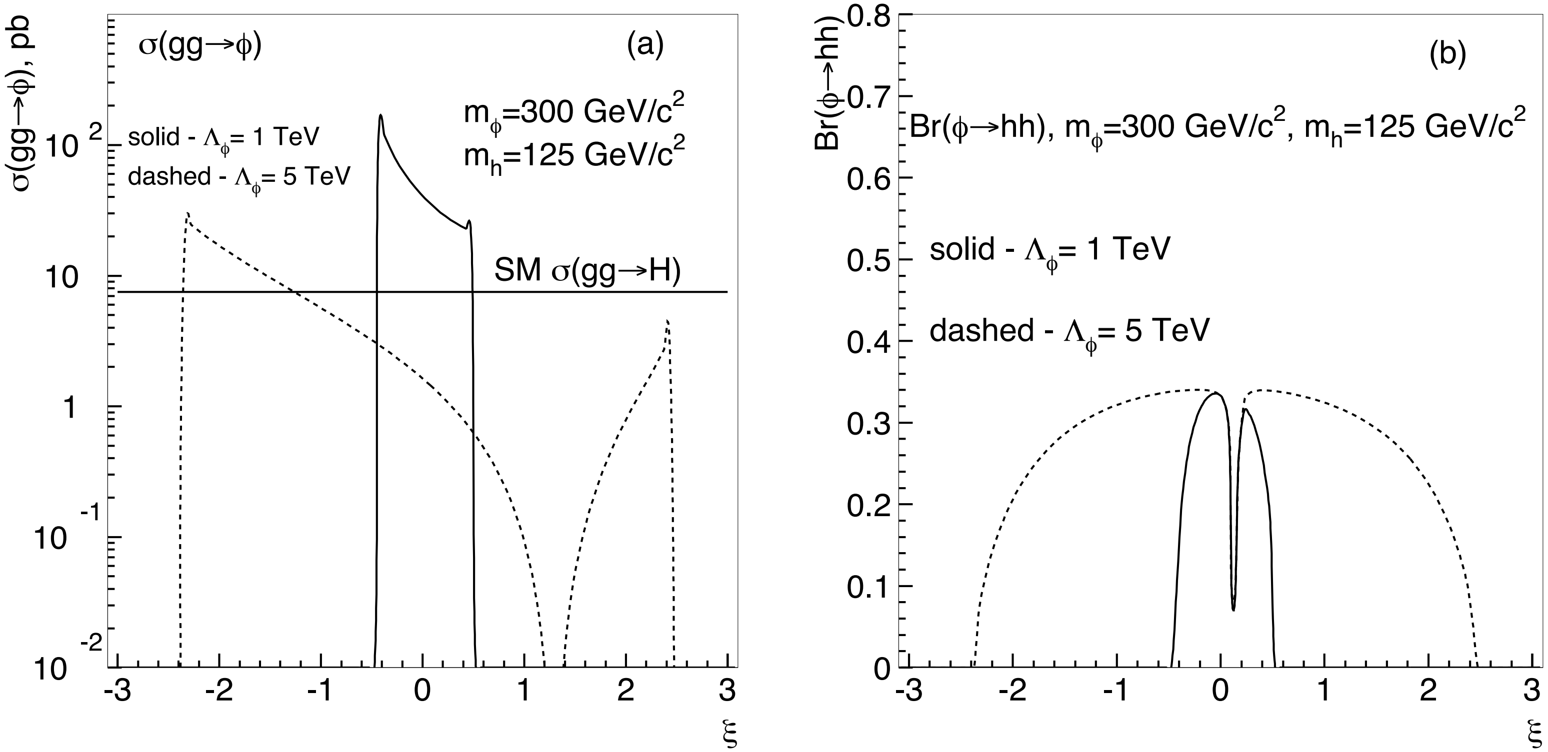
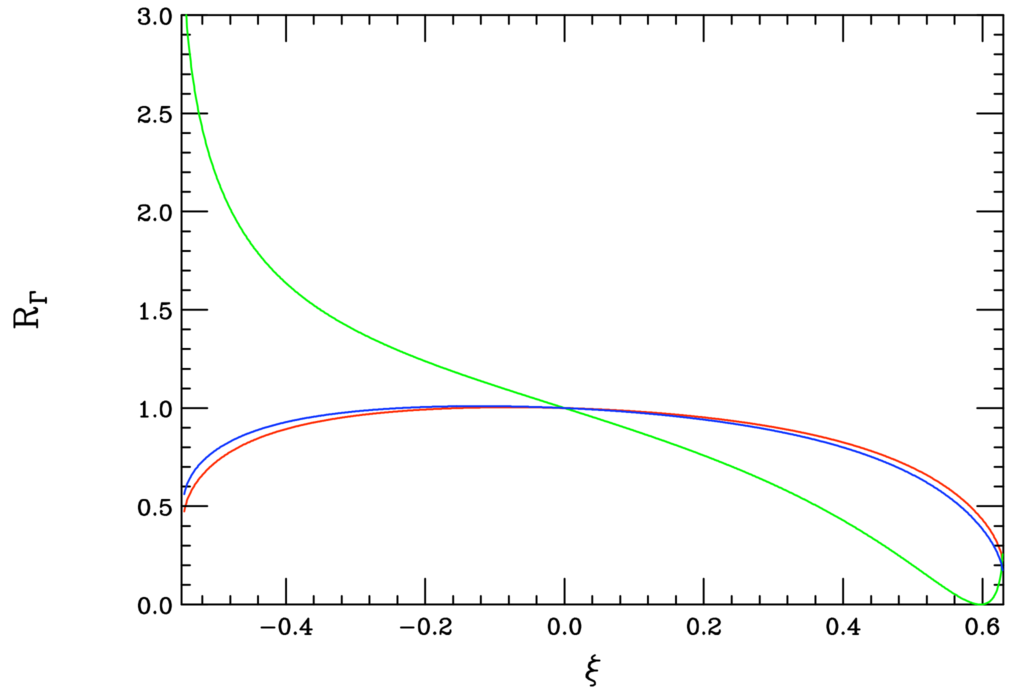


Figure 2: $\sigma(\mathrm{gg} \to \phi)$ (a) and $\mathrm{Br}(\phi \to \mathrm{hh})$ (b) as a function of the parameter ξ for two values of Λ_ϕ, 1 and 5 TeV. On the left plot the cross section of $\mathrm{gg} \to \mathrm{H}_{\mathrm{SM}}$ process for the SM Higgs boson of 300 GeV/c^2 mass is also shown as the horizontal line.



3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.4
−0.2
0.0
0.2
0.4
0.6
R_Γ
ξ

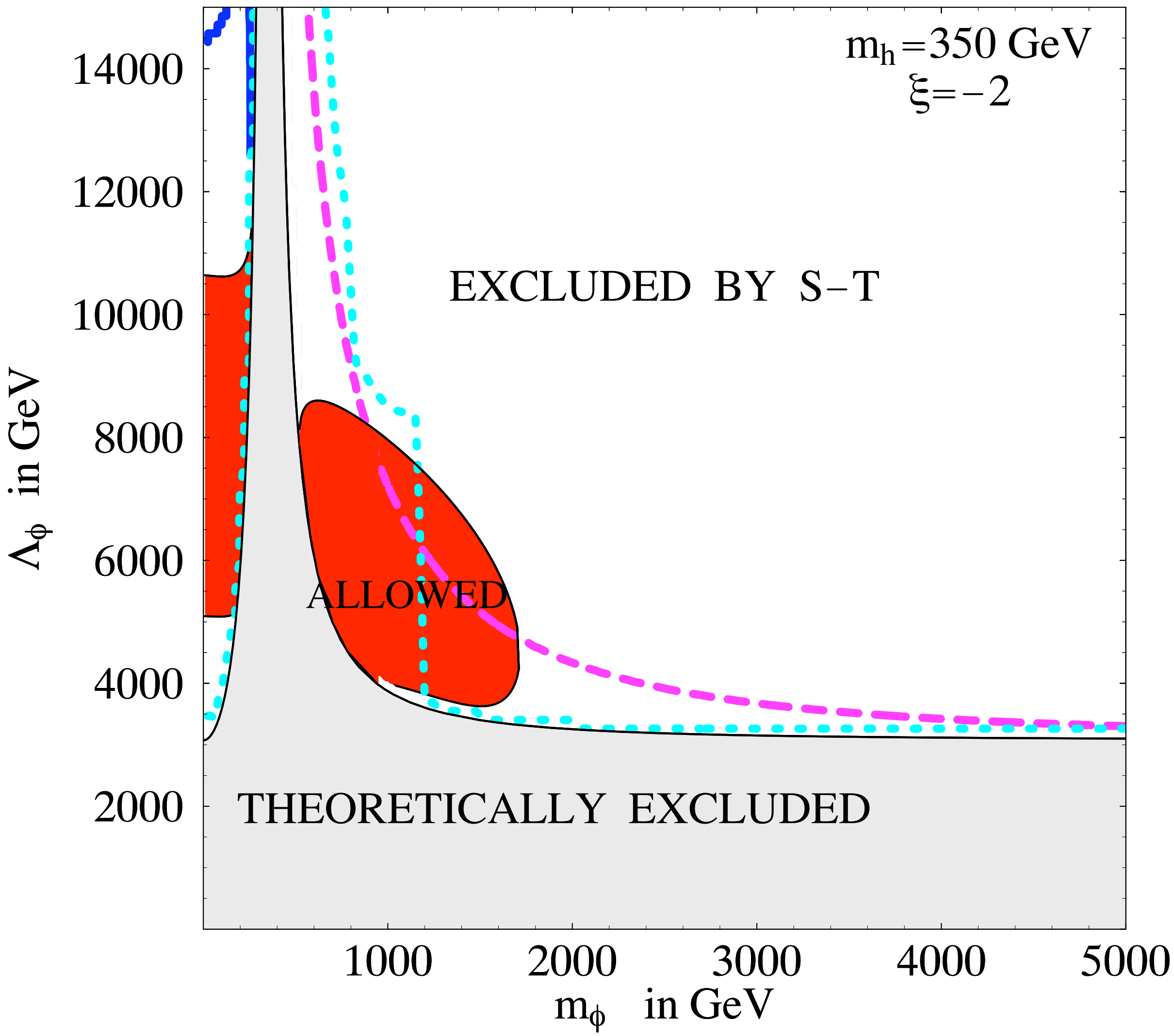
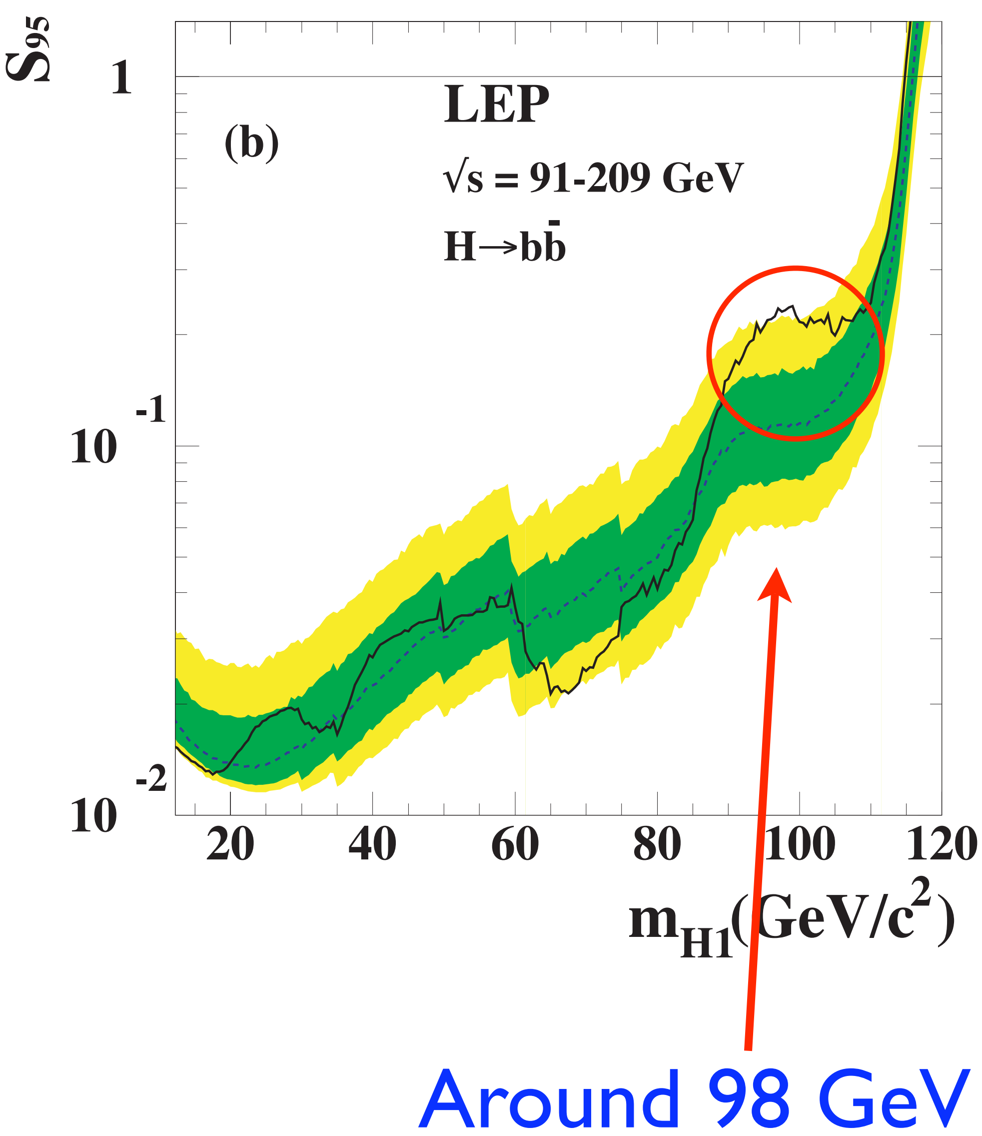


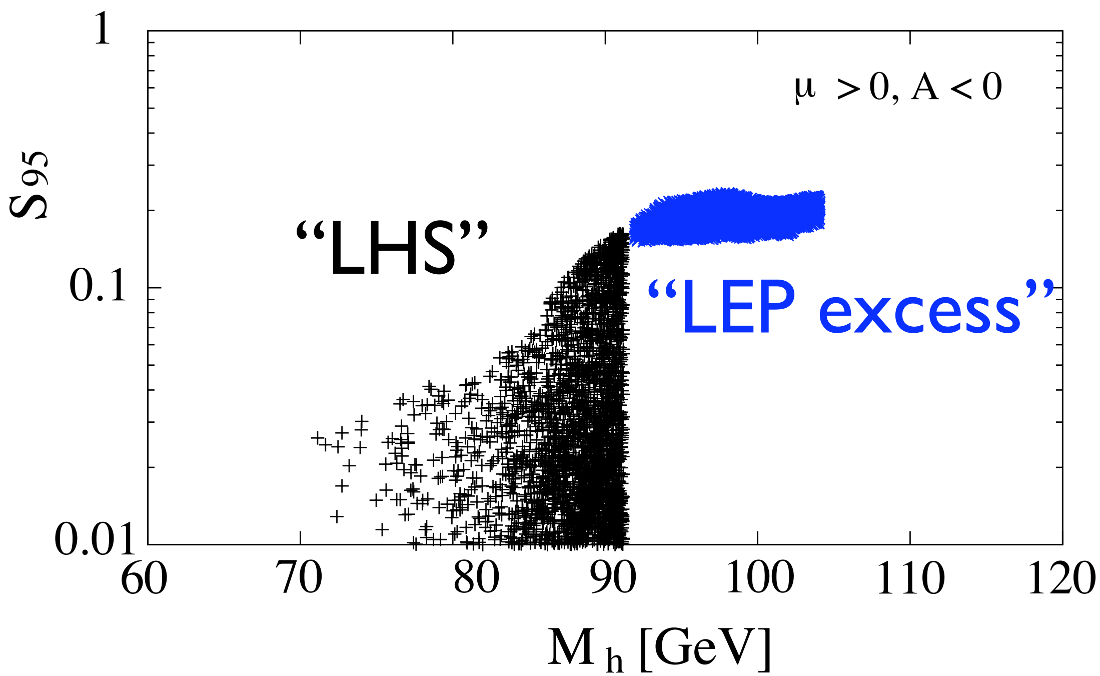
Figure 3: Precision electroweak allowed [solid (red) regions] and disallowed regions (at 90% CL) of the radion mass as a function of Λ_ϕ, while holding fixed $m_h = 350\,\mathrm{GeV}$ and $\xi = -1$. The masses of the Higgs and radion physical eigenstates can be greater than the SM Higgs boson precision electroweak 95% CL upper limit of 219 GeV. The thick (pink) dashed line to the right of the theoretically disallowed tower is the LHC contour for $r^h \equiv N^h_{SD}/N^{SM}_{SD} = 0.9$ – to the right of this contour $0.9 < r^h < 1$. The thick (blue) solid line to the left of the tower is the contour for $r^h = 1.1$ – above this contour $1 < r^h < 1.1$. Between the tower and the thinner dotted (cyan) line, $N^\phi_{SD} > 5$. See text for more details.

Light Higgs scenario (LHS) and "LEP excess" scenario

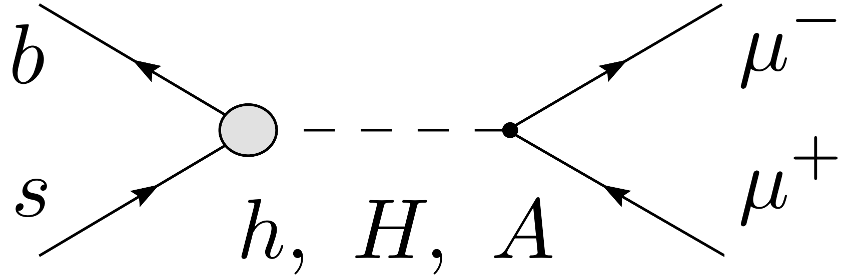
Zh channel $(h \rightarrow b\bar{b})$

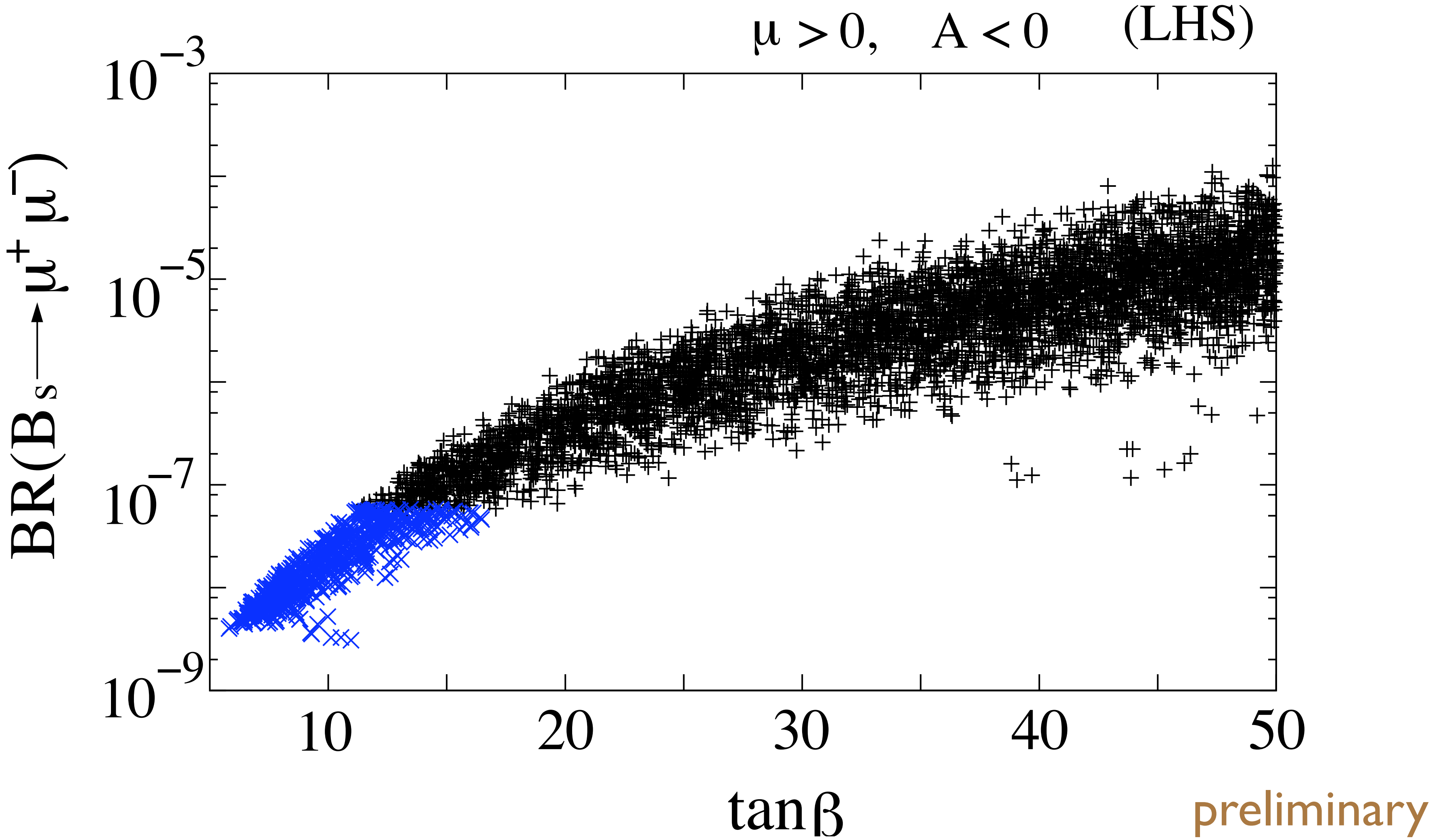
$$S_{95} = \sin^2(\beta - \alpha)\mathrm{BR}(h \rightarrow b\bar{b})$$





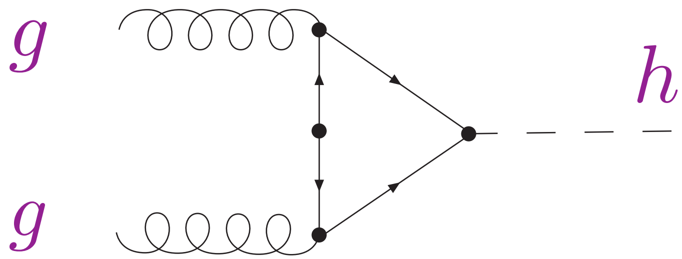
$$B_s \rightarrow \mu^+ \mu^-$$



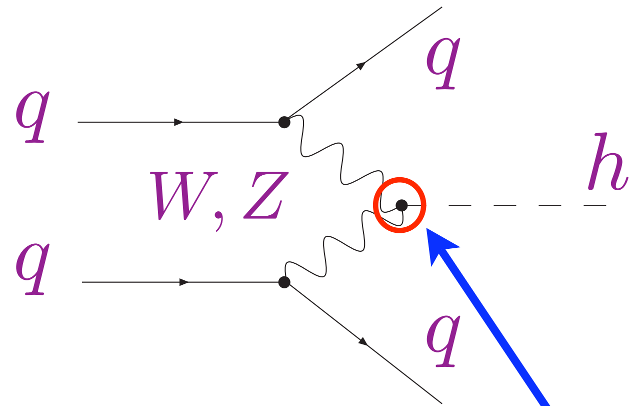


Large $\tan\beta$ region is strongly constrained.

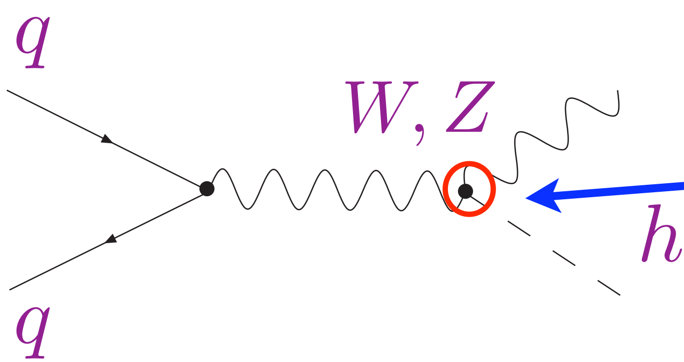
Higgs Production at hadron colliders



gluon fusion (gg)



weak boson fusion (VV)

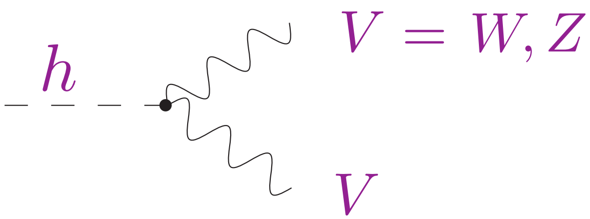


Vh associated production (Vh)

This coupling is suppressed in the LHS

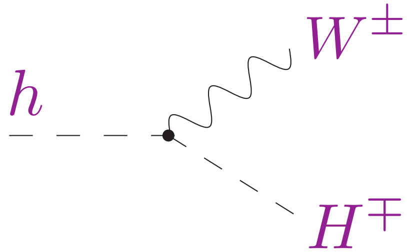
hH^+/AH^+ production at LHC

$\sin(\beta - \alpha)$

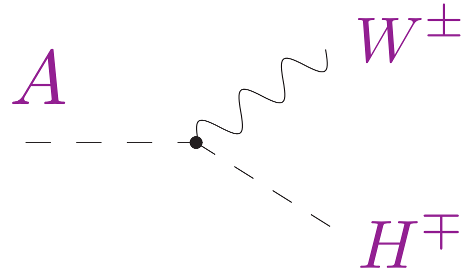


suppressed in LHS

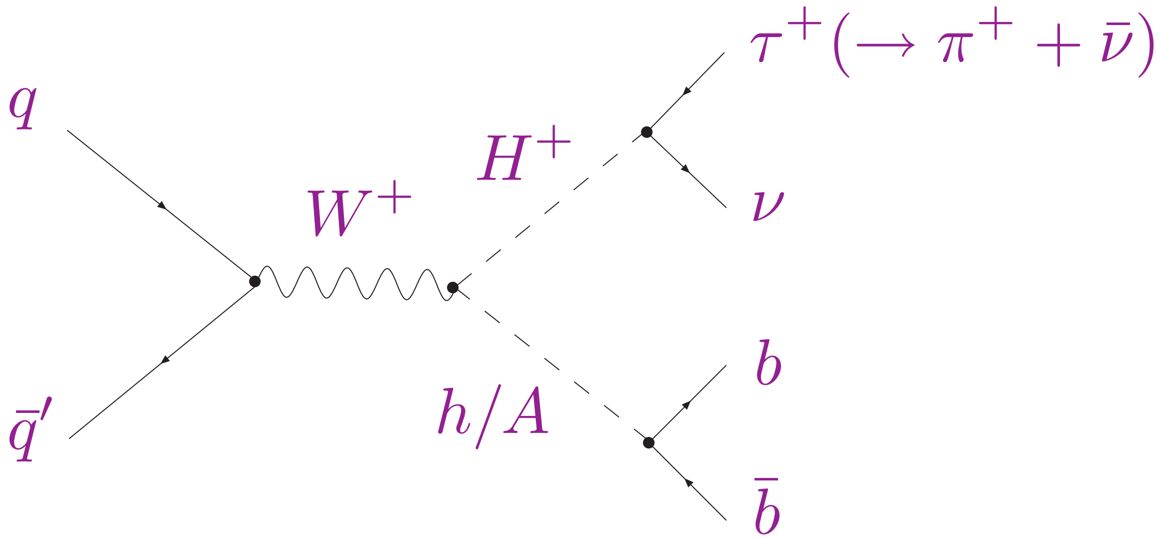
$\cos(\beta - \alpha)$



enhanced in LHS



angle-independent

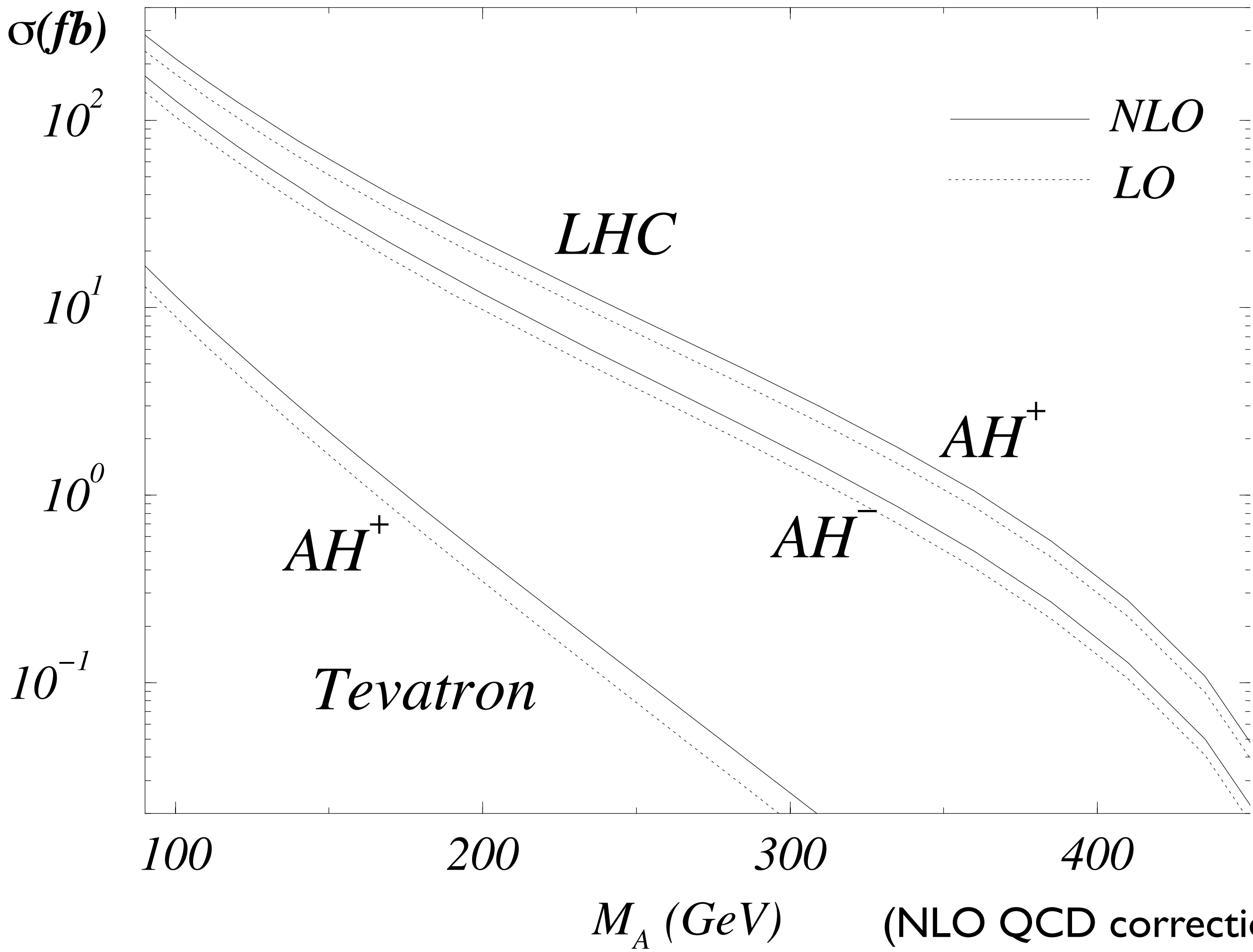


Since all MSSM Higgs bosons are not heavy in LHS, this production can be sizable at LHC.

AH^+ production rate

PLB530,188 (hep-ph/0112165): Kanemura, Yuan

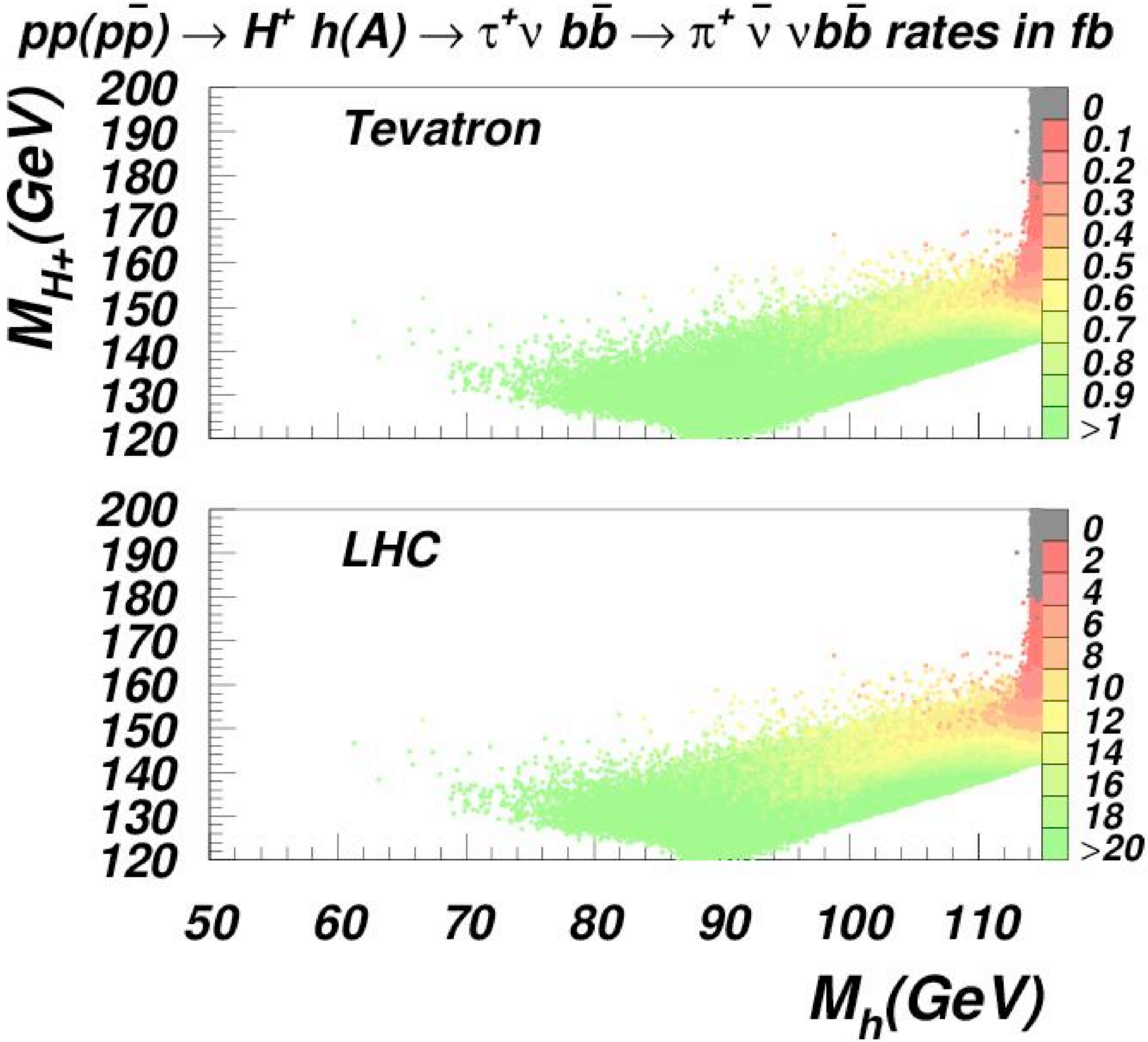
PRD69,075008(hep-ph/0311083): Cao, Kanemura, Yuan



(NLO QCD correction is about 20 %)

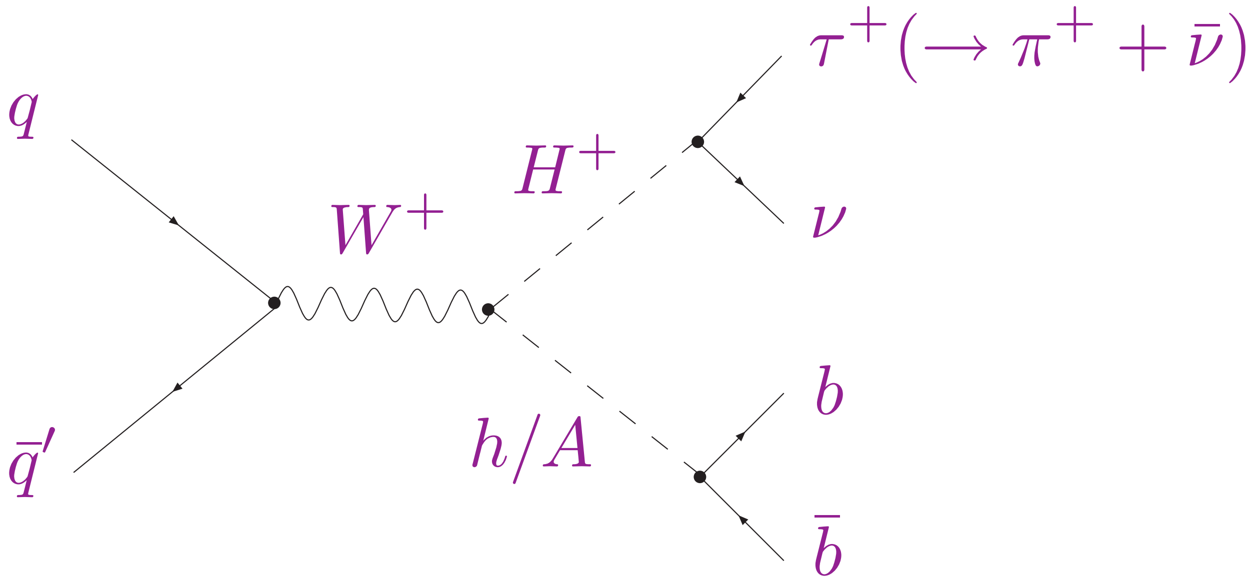
- CP-odd Higgs is light (~100 GeV), the production cross section is big at LHC.
- In addition to AH+ mode, we have hH+ mode in our LHS.

Signature rate at Tevatron and LHC



At LHC, the points with more than 1 fb can be covered.

Signal process



SM background

$$Wb\bar{b} : qq' \to b\bar{b}W^+, W^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu},$$

$$t\bar{b} : qq' \to W^* \to t\bar{b}, t \to bW^+, W^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu},$$

$$WZ : qq' \to W^+Z^0, Z^0 \to b\bar{b}, W^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu}.$$

$$Wg : qg \to q't\bar{b}, t \to W^+b, W^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu},$$

$$t\bar{t} : qq(gg) \to t\bar{t}, t \to W^+b, W^+ \to \tau^+\nu, \tau^+ \to \pi^+\bar{\nu}, \bar{t} \to \bar{b}W^-$$

Effect of cuts

TABLE II: Numbers of AH^+ signal and background events for the sample point in the $b\bar{b}\pi^+ \not{E}_T$ channel at the LHC with an integrated luminosity of $100\,\text{fb}^{-1}$. The b-tagged efficiency defined in Eq. 55 is included and the kinematics cuts listed in each column are applied sequentially.

	Basic cut	$\not{E}_T > 50\,\text{GeV}$	$p_T^\pi > 40\,\text{GeV}$	$\lvert m_{b\bar{b}} - m_A\rvert < 10\,\text{GeV}$	$m_T > 80\,\text{GeV}$
AH^+	214	169	107	103	40
hH^+	259	199	122	1	0
$Wb\bar{b}$	3765	1229	394	30	2
WZ	361	128	40	10	1
$t\bar{b}$	778	387	106	8	0
Wg	298	153	43	2	0
$t\bar{t}$	50	37	8	1	0
Signal (S)	214	169	107	103	40
Background (B)	5511	2133	713	52	3
S/B	0.04	0.08	0.15	1.98	13.33
$S/\sqrt{B}$	2.88	3.66	4.01	14.28	23.09

Basic cuts $p_T(b, \bar{b}, \pi^+) > 15$ GeV, $|\eta(b, \bar{b}, \pi^+)| < 3.5$,

$\Delta R > 0.4$ between any two observable final state partons

$\Delta R\ (\equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$ $\Delta\phi$ and $\Delta\eta$ are the separation in azimuthal angle and rapidity, respectively.

TABLE III: Numbers of hH^+signal and background events for the sample point in the $b\bar{b}\pi^+ \not{E}_T$ channel at the LHC with an integrated luminosity of $100\,\mathrm{fb}^{-1}$. The b-tagged efficiency defined in Eq. 55 is included and the kinematics cuts listed in each column are applied sequentially.

	Basic cut	$\not{E}_T > 50\,\mathrm{GeV}$	$p_T^\pi > 40\,\mathrm{GeV}$	$\lvert m_{b\bar{b}} - m_h\rvert < 10\,\mathrm{GeV}$	$m_T > 80\,\mathrm{GeV}$
hH^+	259	199	122	119	49
AH^+	214	169	107	1	0
$Wb\bar{b}$	3765	1229	394	39	3
$t\bar{b}$	778	387	106	8	0
Wg	298	153	43	4	0
$t\bar{t}$	50	37	8	1	1
WZ	361	128	40	9	1
Signal (S)	259	199	122	119	49
Background (B)	5466	2103	698	62	5
S/B	0.05	0.09	0.17	1.92	9.8
$S/\sqrt{B}$	3.50	4.34	4.62	15.11	21.9

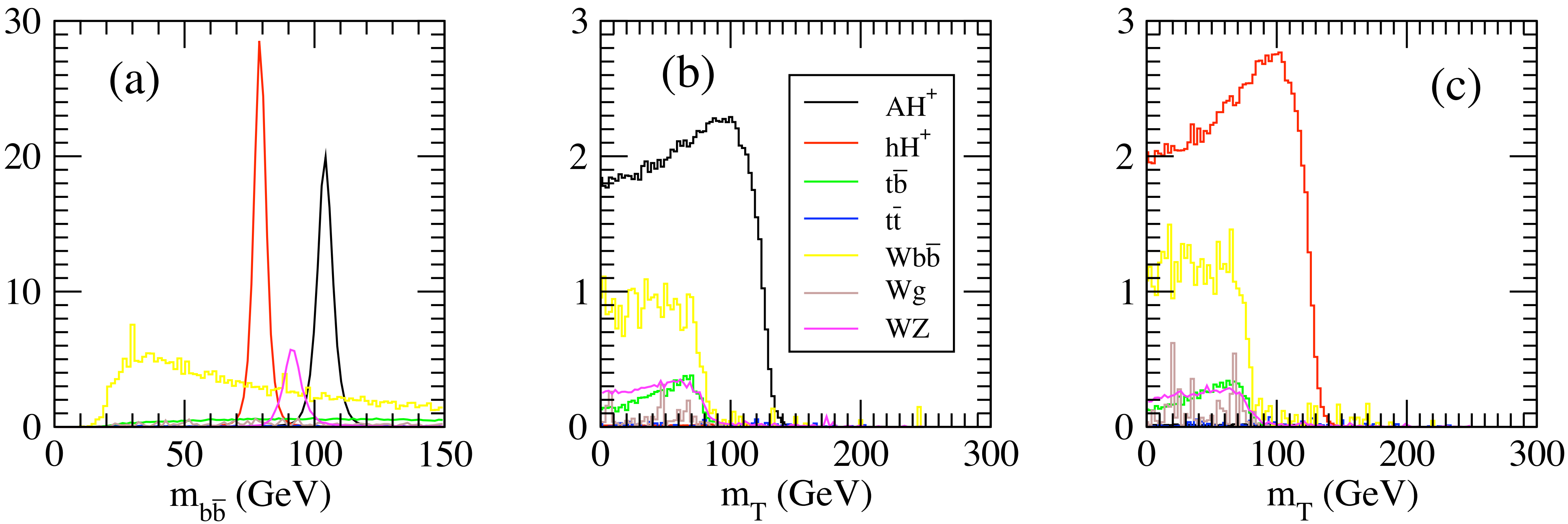


FIG. 30: Distributions of invariant mass $m_{b\bar{b}}$ (after imposing the basic, $\not{E}_T$ and p_T^π cuts) and transverse mass m_T (after imposing the basic, $\not{E}_T$, p_T^π and the Higgs mass window cuts): (b) AH^+ and (c) hH^+. Here $m_T = \sqrt{2p_T^\pi E_T^{\rm mis}(1-\cos\phi')}$

Significance contour of AH^{+}/hH^{+}

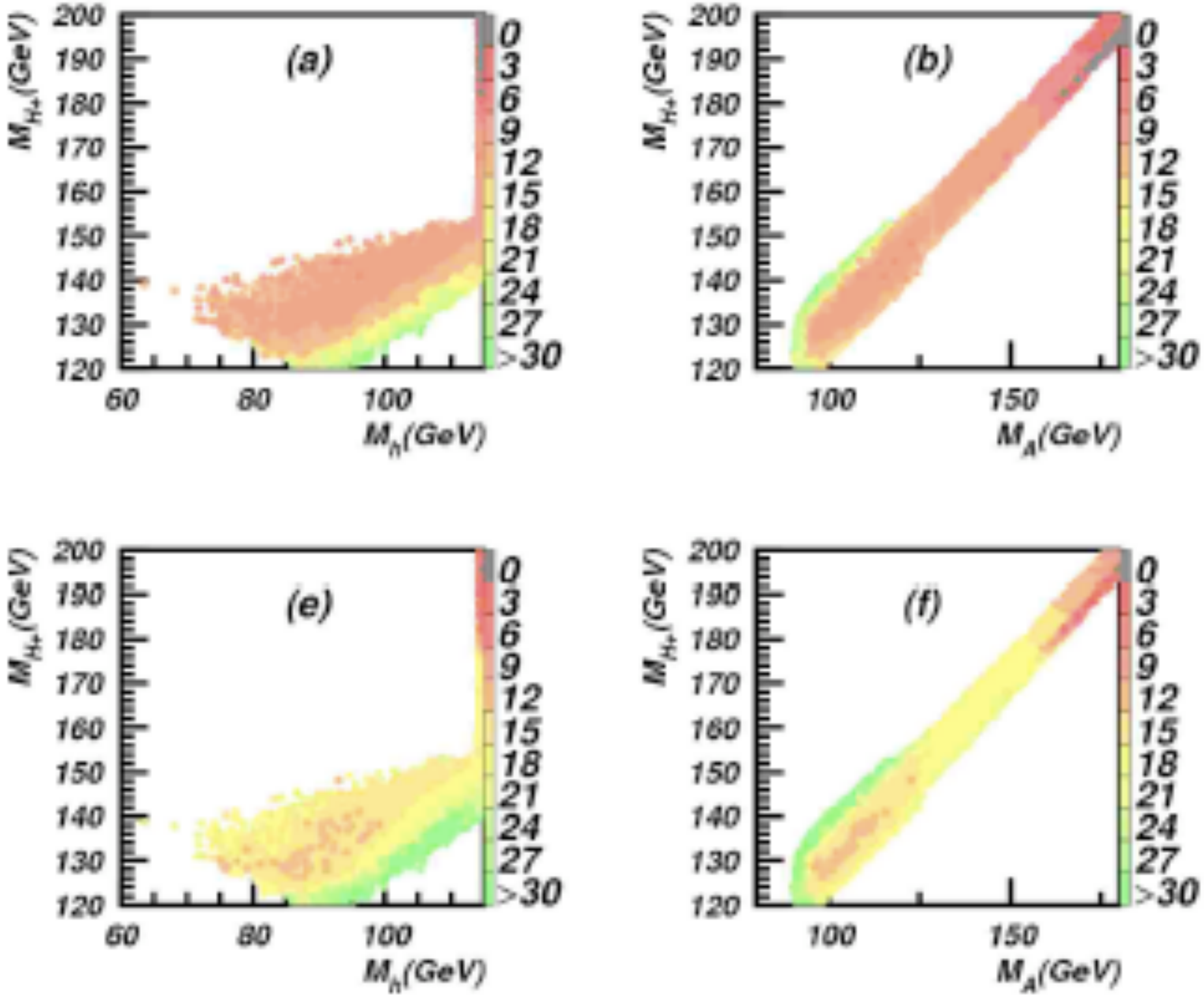


FIG. 32: Contours of the significance and event numbers of the AH^+/hH^+ processes at LHC after imposing the mass window cut (first row) and the transverse mass cut (second row) in the case of positive μ.

To reach 5-sigma significance, only 5-10 fb^-1 integrated luminosity is required!