The Supersymmetric Limit of Electroweak Symmetry Breaking

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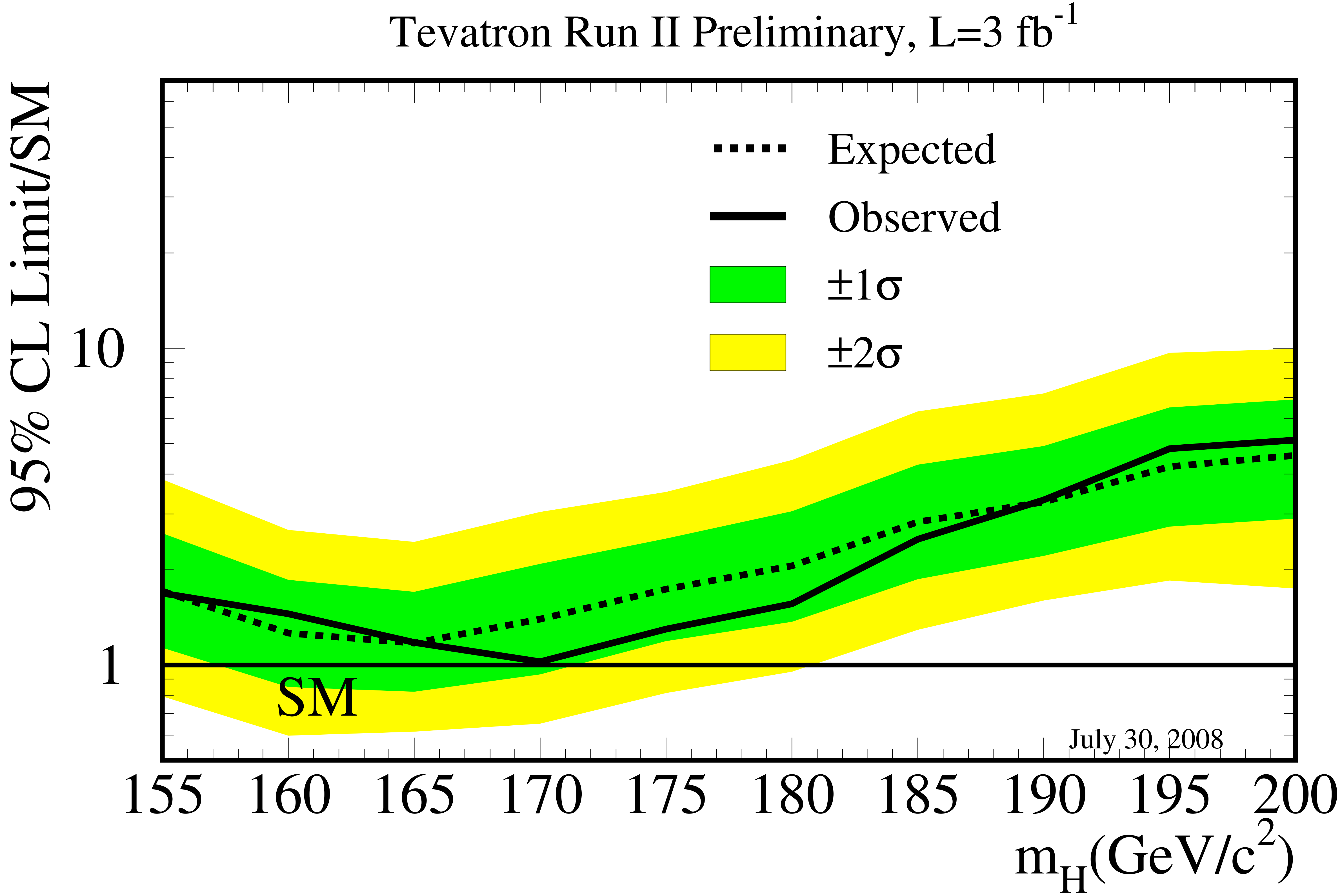
The SM Higgs ruled out at 170 GeV!



The MSSM Scalar Sector

- First choice for non-SM Higgs searches

2 parameters $\longrightarrow$ Physics of 4 fields

(m_A, t_β) $\quad\quad$ $(h^0, H^0, H^\pm, A^0)$

a generic theory has 7 more parameters.

- Expectation:

Looking for the MSSM Higgs Boson
is just like
looking for the SM Higgs Boson.

MSSM (CP-even) Higgs properties

- Very Light SM-like Higgs mass

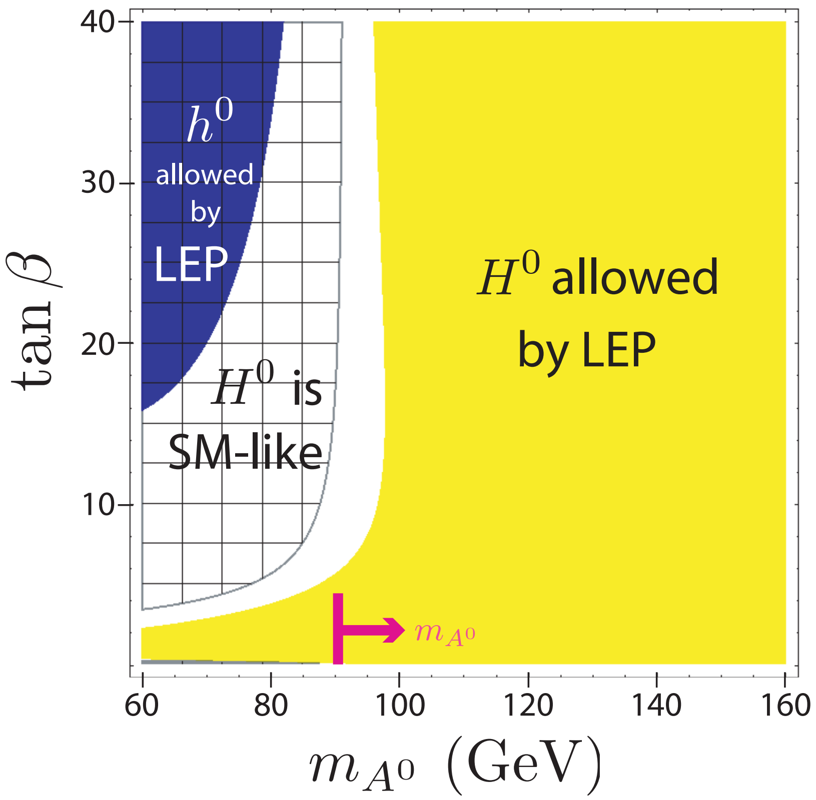
$m_{h^0} < M_Z$ at tree-level

$m_{h^0} \leq 130\ \mathrm{GeV}$ with %-ish tuning

(χ^0, χ^+)

MSSM (CP-even) Higgs properties

- LEP 2b bounds $(m_{H^0} \geq m_{h^0})$



$$M_{\tilde{t}} \sim m_t$$

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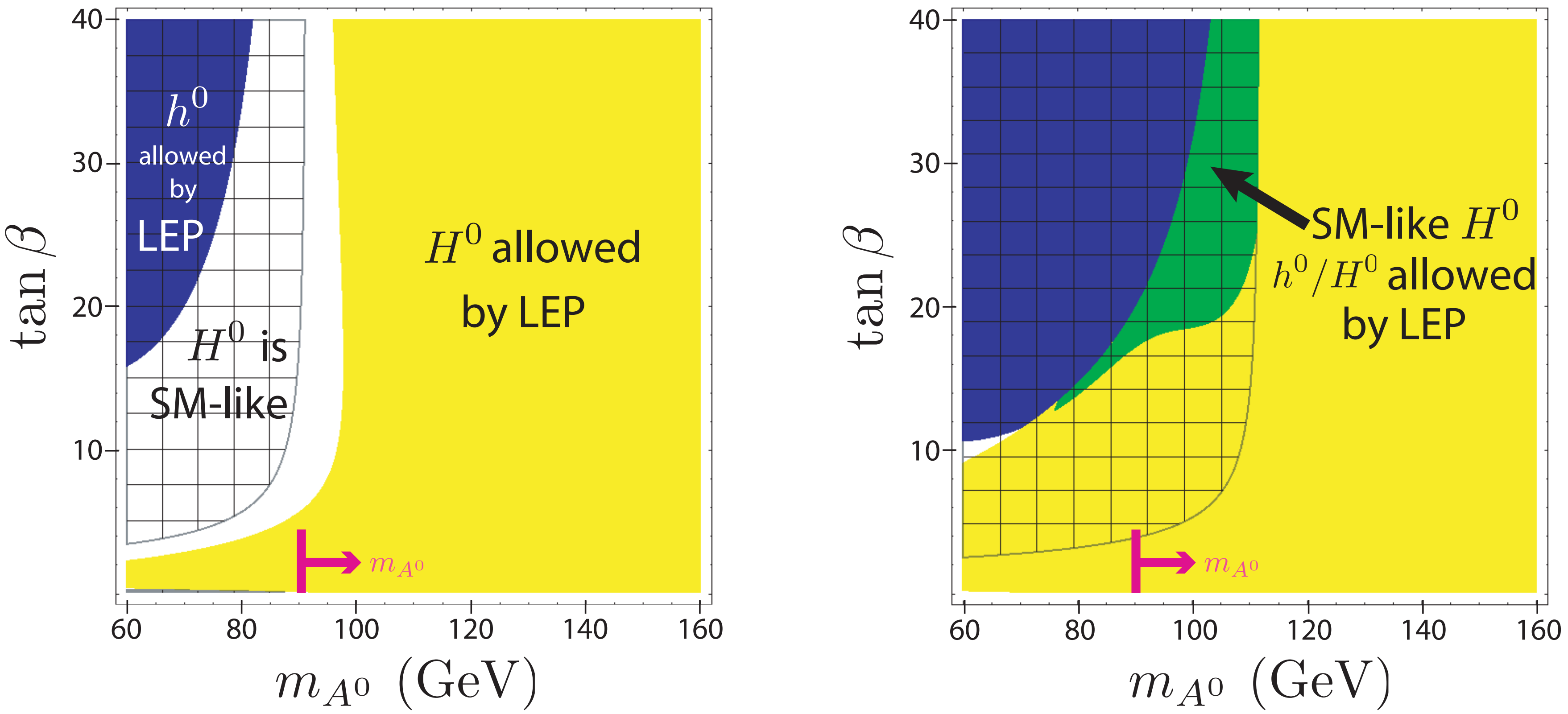

$M_{\tilde{t}} \sim m_t$

$M_{\tilde{t}} \sim 400$ GeV

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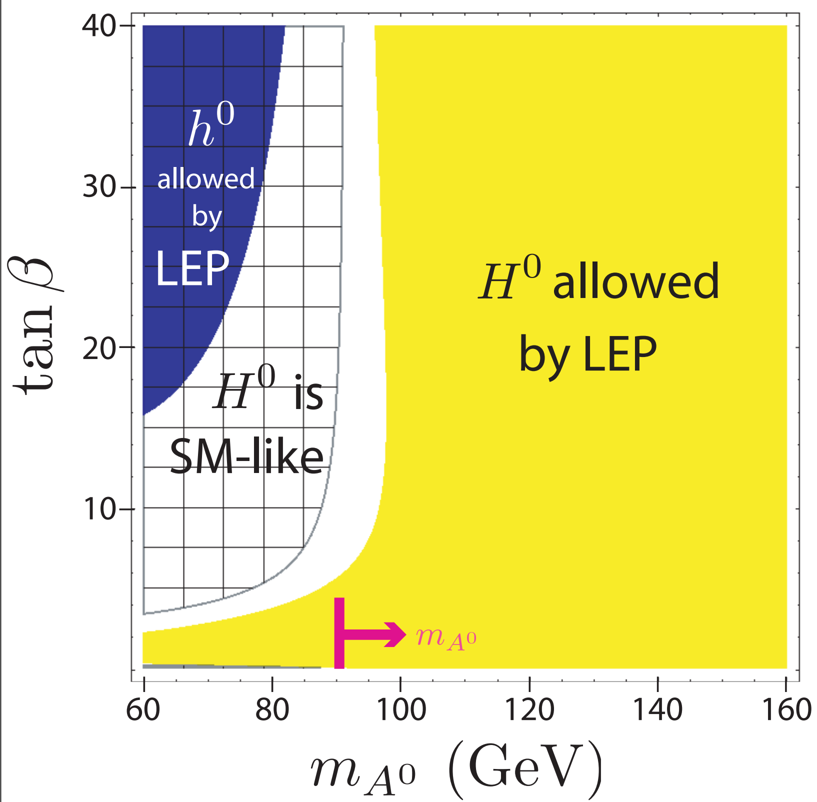

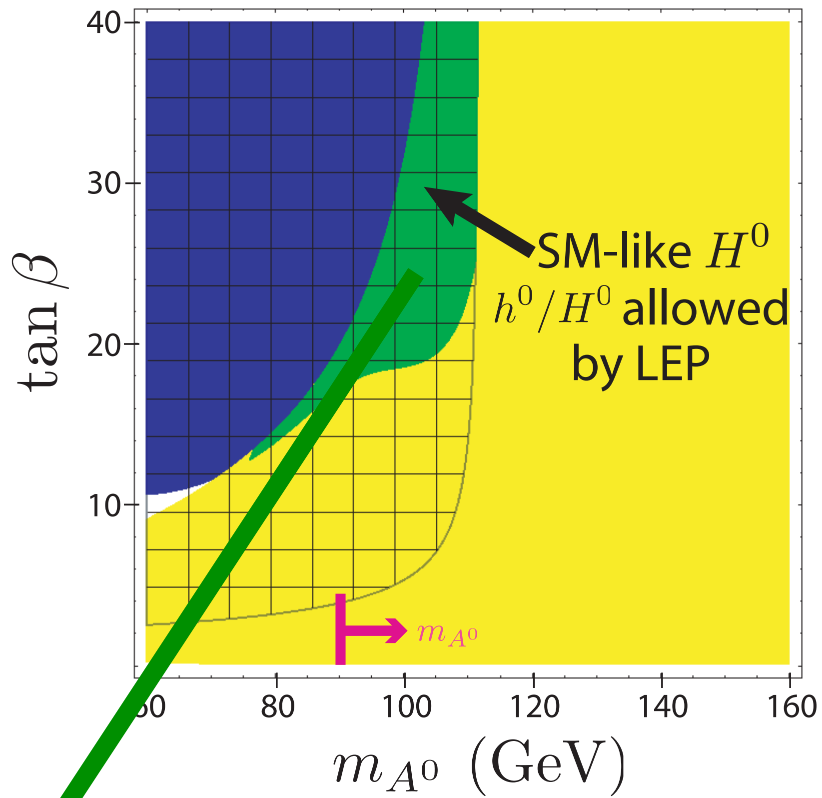

$$M_{\tilde{t}} \sim m_t \qquad\qquad M_{\tilde{t}} \sim 400 \text{ GeV}$$

$$m_A^2 < M_Z^2 \rightarrow \frac{b}{m_Z^2} \ll \frac{1}{20} \quad \& \quad \frac{b}{|m_u^2 - m_d^2|} \ll \frac{1}{30}$$

MSSM (CP-even) Higgs properties

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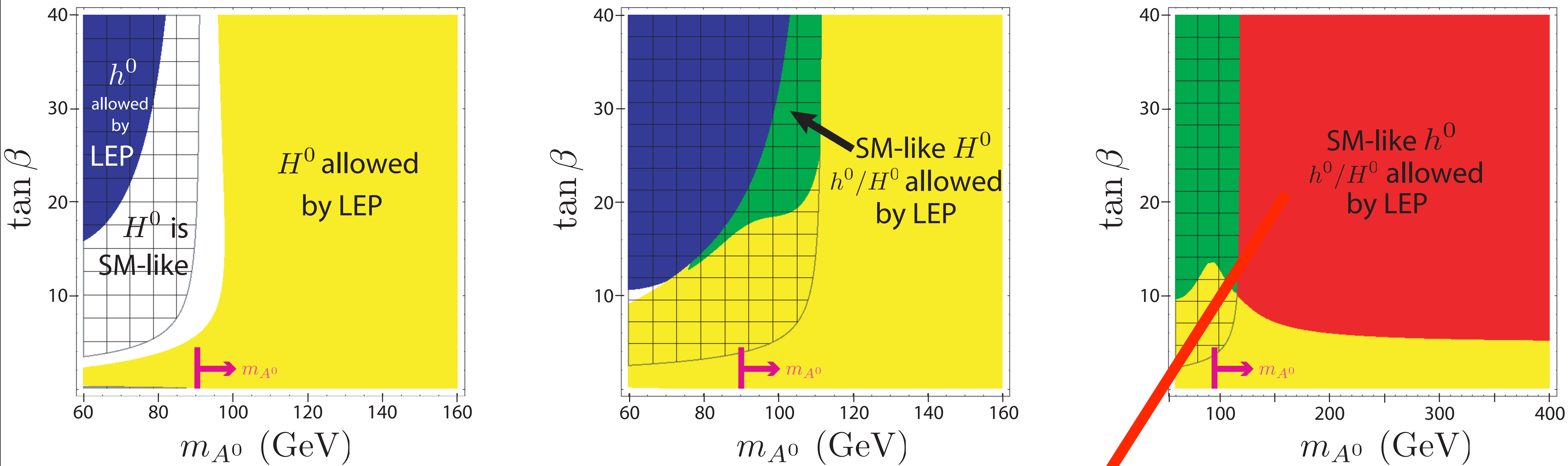

$M_{\tilde{t}} \sim m_t \qquad M_{\tilde{t}} \sim 400$ GeV $\qquad M_{\tilde{t}} \sim 600$ GeV

$$m_A \simeq m_H \simeq m_{H^\pm} \left[\pm \mathcal{O}\left(\frac{m_Z^2}{m_A} \right) \right] \qquad g_{H^0 ZZ} \sim 0 + \mathcal{O}\left(\frac{m_Z^2 s_\beta^4}{4 m_A^2} \right)$$

Decoupling limit ~ h^0 is SM-like

Beyond The MSSM Scalar Sector

- Can use strong-coupling to increase m_{h^0}

$$m_{h^0} \sim 300 \text{ GeV}$$

Haber-Sher, Espinosa-Quiros, Randall,
P.B. et al., “The Fat Higgs”, ...

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- Can evade LEP bounds via singlet production

NMSSM, Dermisek-Gunion, Chang-Fox-Weiner

qualitative shift in Higgs physics!

$$h^0 \to 2a \to 4b, 4\tau, 2b2\tau, \ldots$$

Outline

1. Supersymmetric-EWSB (sEWSB)

   Defined; Qualitative structure; LEP-motivated; UV complete example;

2. An Effective Field Theory approach to sEWSB

   MSSM degrees of freedom only; simple, surprisingly under control; very rich vacuum structure; moving away from the SUSY-breaking limit

3. Higgs searches in sEWSB

   The heavier higgs, H^0, is naturally SM-like;

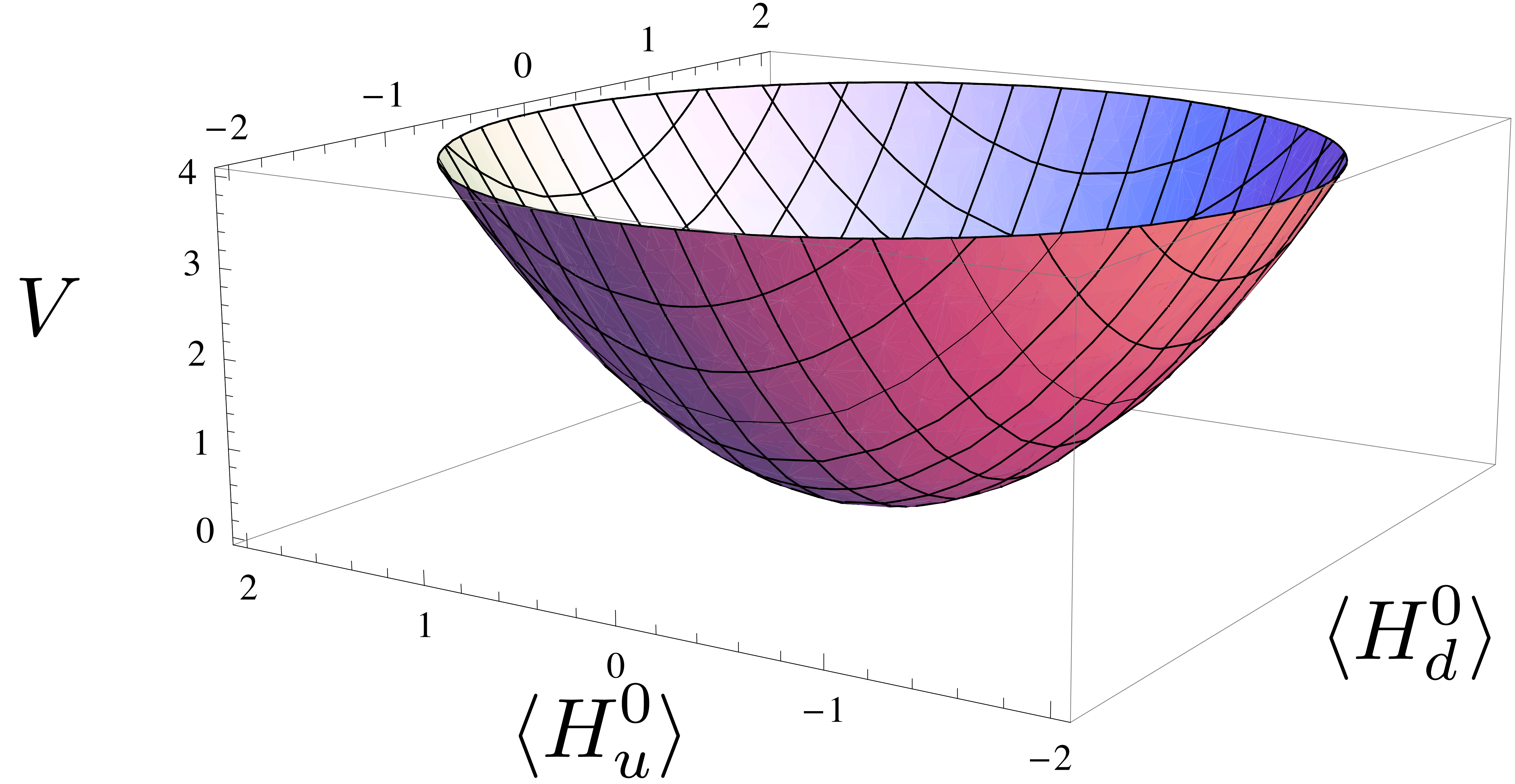
   $H^0 \to h^0 h^0, H^0 \to \chi\chi$

   NLSP Chargino

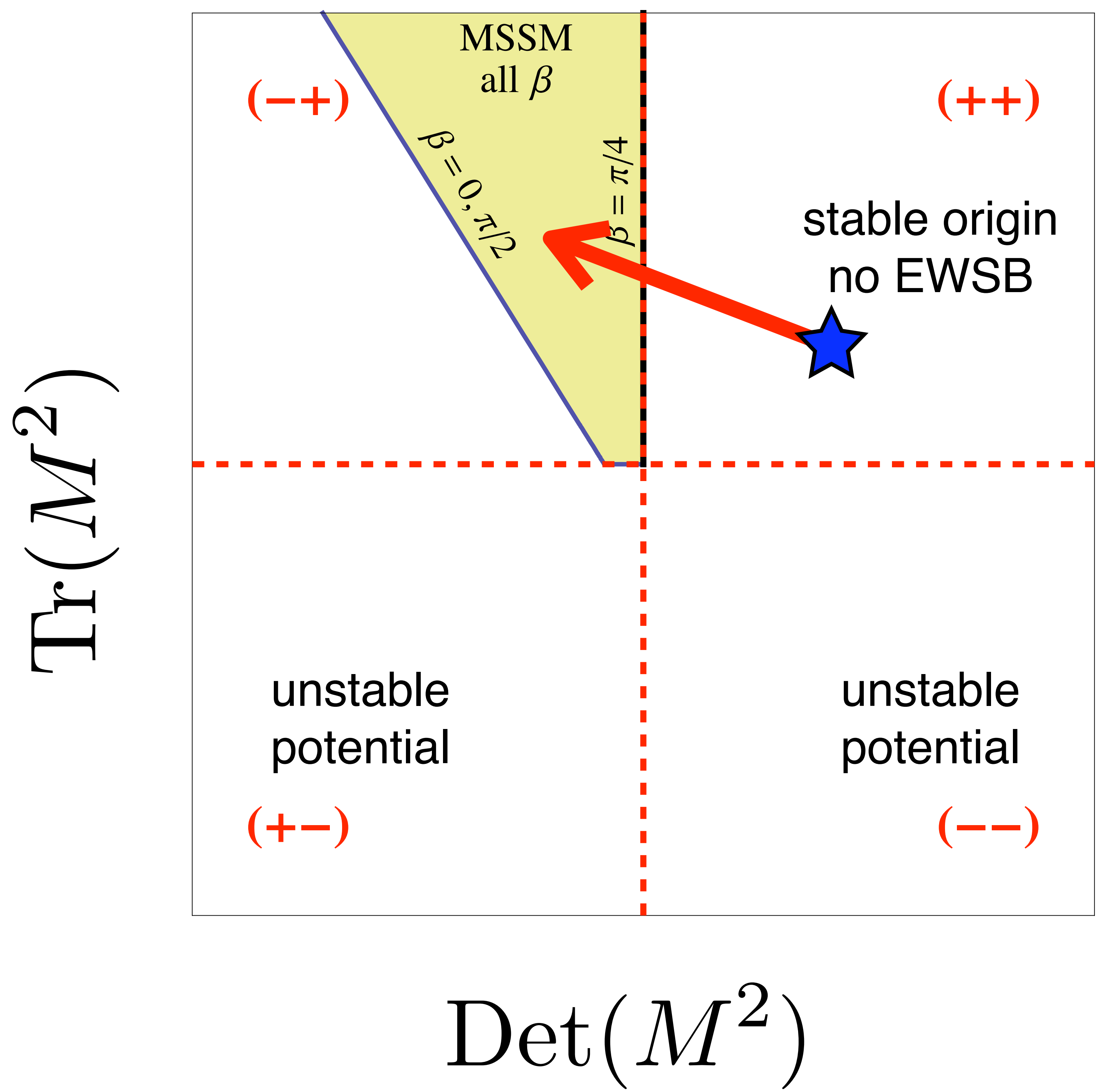
The MSSM

No SUSY-breaking ---> No EWSB

$$W = \mu H_u H_d \to |\mu|^2 |H|^2$$



Radiative EWSB



$$t_\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

$$\mathrm{Tr} = -\frac{1}{2} M_Z^2 - \frac{2\sec^2(2\beta)}{M_Z^2}\mathrm{Det}$$

★ No EWSB w/o SUSY breaking

$m_{H_u}^2$ driven negative by top loops

Supersymmetric EWSB (sEWSB)

SUSY-breaking --> 0, EWSB still occurs

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SUSY-breaking --> 0, EWSB still occurs

general features

--In the SM, massive vector fields 'eat' a real scalar

$$H = e^{iX\theta}\tilde{H}$$

--With sEWSB, massive vector superfields 'eat' an entire chiral superfield.

$$H_i = e^{iX\Theta}\tilde{H}_i \qquad \Theta \supset (\theta + i\theta', \psi_\theta)$$

$$M_{H^\pm} = M_{\chi^\pm} = M_{W^\pm} \qquad M_{h^0} = M_{\chi^0} = M_Z$$

Supersymmetric EWSB (sEWSB)

SUSY-breaking --> 0, EWSB still occurs

general features

--In the SM, a real 'radial' mode remains which contains the SM-like Higgs.

$$\tilde{H} = H_{SM}$$

--With sEWSB, a 'super-radial' mode remains (an entire chiral superfield) which contains the SM-like Higgs, a CP-odd Higgs, and a neutralino

$$\tilde{H} = (H_{SM}, A^0, \chi'^0)$$

Supersymmetric EWSB (sEWSB)

SUSY-breaking --> 0, EWSB still occurs

general features

--In the SM, the Higgs mass is determined by the curvature of the potential.

--With sEWSB, the superfield Higgs mass is determined by the superpotential.

The Kahler potential: $g^2 D^2 \sim \left(\tilde{H}_i^\dagger T^a \tilde{H}_i \right)^2$

does not contain a mass term for $\tilde{H}$

Supersymmetric EWSB (sEWSB)

Summary:

Mass	Scalars	Fermions	Vectors
0	—	1 majorana	A_μ
m_W	$H^\pm$	2 Dirac	$W_\mu^\pm$
m_Z	h^0	1 Dirac	Z_μ
?	H_{SM}, A^0	1 majorana	—

No real decoupling limit (strong coupling limit)

Supersymmetric EWSB (sEWSB)

Example of a Twisted Custodial Symmetry

Gerard & Herquet

$$\Sigma_1 = \begin{pmatrix} v + H_{SM} & 0 \\ 0 & v + H_{SM} \end{pmatrix} \to U_L \Sigma_1 U_R^\dagger$$

Preserves an SU(2) Custodial, but

$$\Sigma_2 = \begin{pmatrix} h^0 - iA^0 & H^+ \\ H^- & h^0 + iA^0 \end{pmatrix} \to U_L \Sigma_2 \left(X^\dagger U_R^\dagger X \right)$$

Custodial triplet

$X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ or $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ $\quad$ $(H^\pm, A^0)$ or $(H^\pm, h^0)$

Supersymmetric EWSB (sEWSB)

Two theoretical motivations for study, but don't forget:

Supersymmetric EWSB (sEWSB)

Two theoretical motivations for study, but don't forget:

Unlike the MSSM, the SM-like Higgs mass is NOT determined by gauge couplings (g_w).

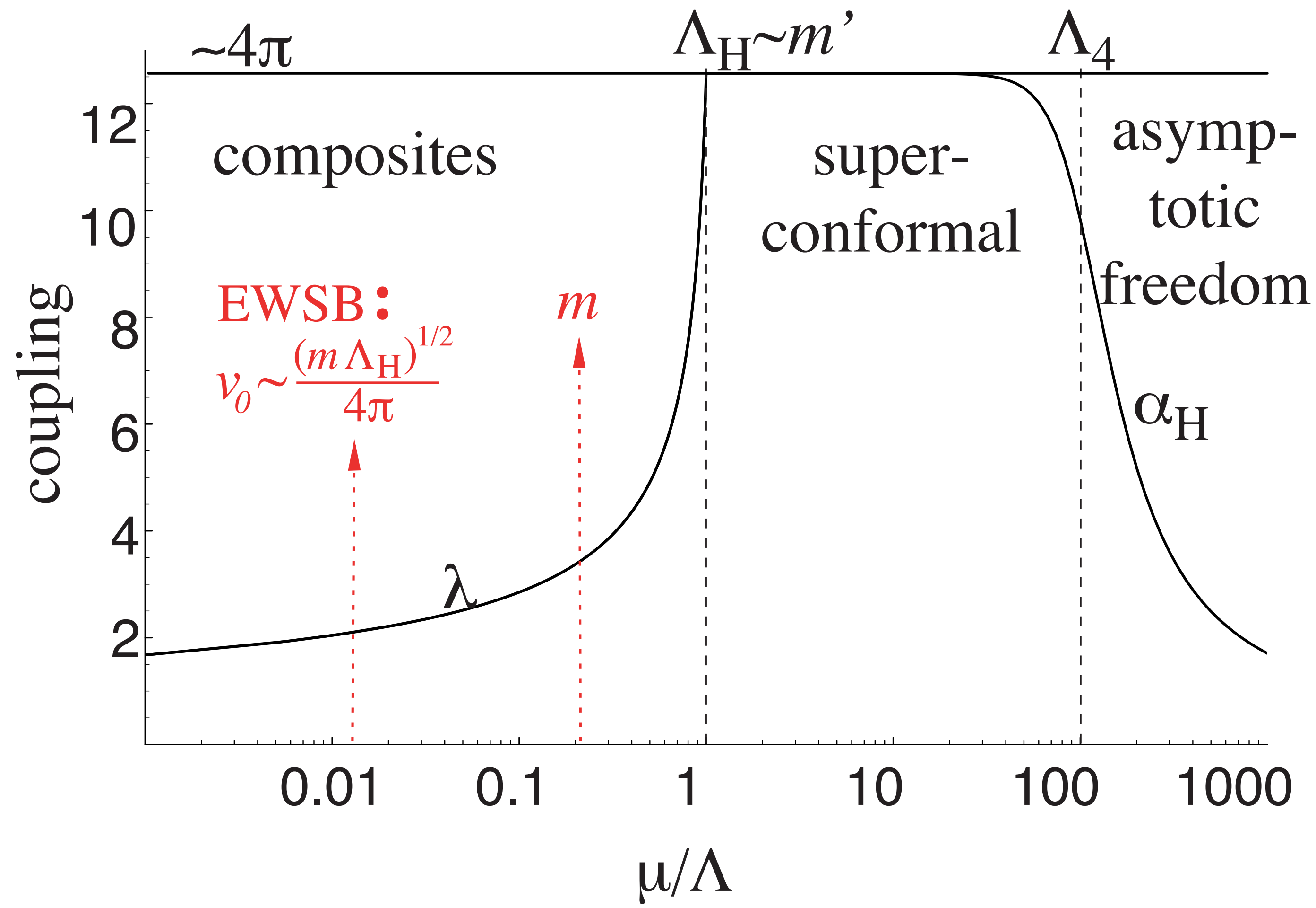
Should expect the SM-like Higgs mass to be related to M_Z as it is in the Standard Model (unitarity).

Very straightforward resolution to the SUSY hierarchy problem in sEWSB vacua.

Concrete example: Fat Higgs

Solves the SUSY-hierarchy problem

Harnik, Kribs, Larson, Murayama



$$\rightarrow W \supset \lambda N \left(H_u H_d - v_0^2\right)$$

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An effective field theory of sEWSB

The simplest SUSY extension of the MSSM has sEWSB!

$$W \supset \mu H_u H_d + \frac{1}{2\mu_s}(H_u H_d)^2$$

-- μ_S is the scale of unknown (SUSY) UV physics

$$\mu \ll \mu_S$$

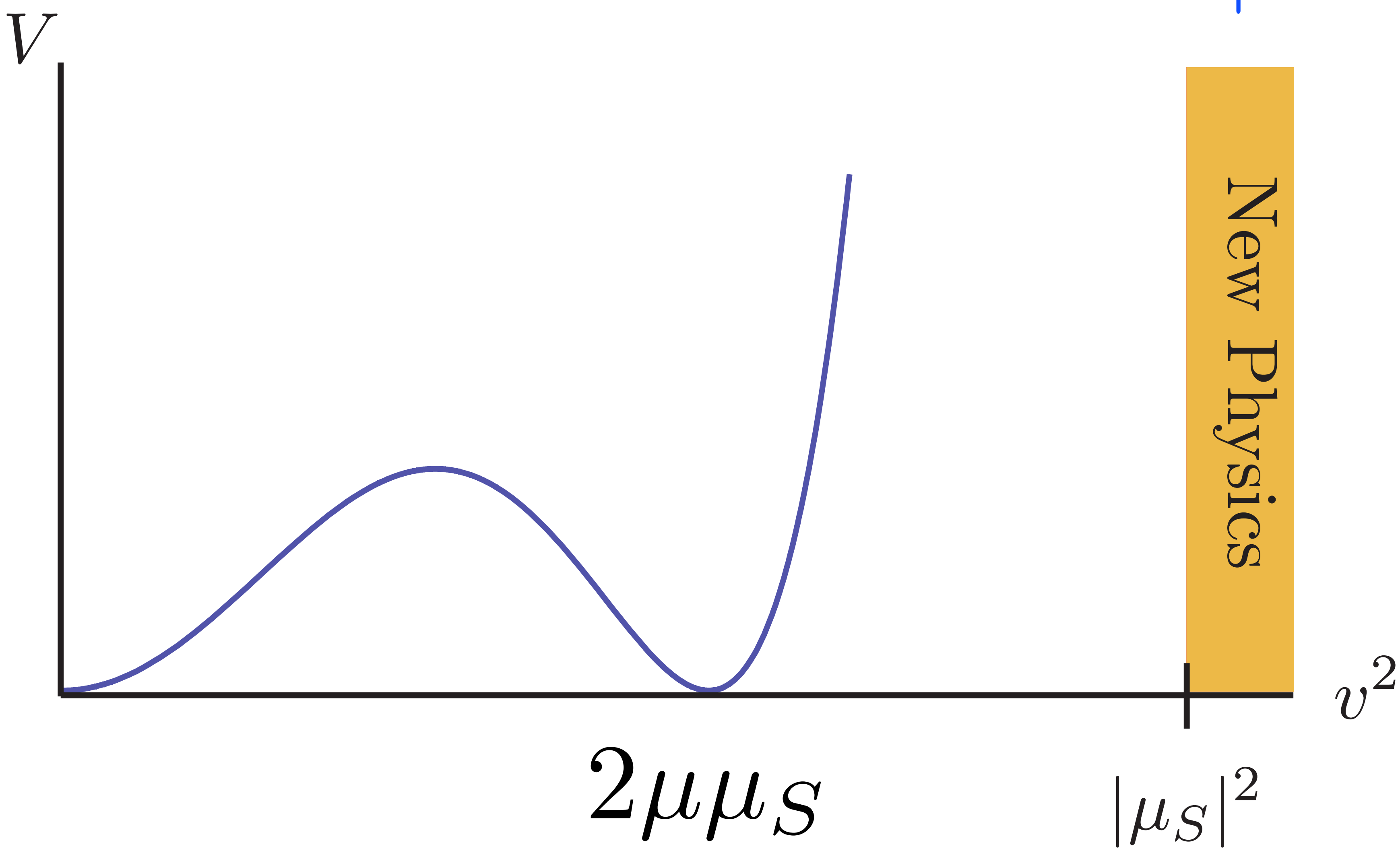
-- one (but not the only) example is a SUSY singlet

$$W \supset \lambda S H_u H_d + \mu_S S^2$$

An effective field theory of sEWSB

$$W \supset \mu H_u H_d + \frac{1}{2\mu_s}(H_u H_d)^2$$

$$V = \left(|H_u^0|^2 + |H_d^0|^2\right)\left|\mu - \frac{1}{\mu_S} H_u^0 H_d^0\right|^2$$



$$\tan\beta = 1$$

$$\langle H_u^0 H_d^0 \rangle = \mu\mu_S$$

D-terms give mass to $H^{\pm}, h^0$

Mass of the super-radial mode

$$H_u^0 = \frac{e^{-iT\Theta}}{\sqrt{2}}\left(\tilde{H} + v\right) \quad H_d^0 = \frac{e^{iT\Theta}}{\sqrt{2}}\left(\tilde{H} + v\right)$$

$$W \supset \mu H_u H_d + \frac{1}{2\mu_s}(H_u H_d)^2 = \frac{1}{2}\left(2\mu\right)\tilde{H}^2$$

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m_Z	h^0	1 Dirac	Z_μ
$2\|\mu\|$	H_{SM}, A^0	1 majorana	—

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Mass of the super-radial mode

$$2|\mu| > M_Z \to H_{SM} = H^0$$

Inverted scalar hierarchy

Validity of the Effective Field Theory

Already a surprising result:

a 'non-renormalizable' VEV!

--Consider a the SM-Higgs potential

$$V \sim -m^2 H^2 + \lambda H^4 \qquad \langle H^2 \rangle \sim \frac{m^2}{\lambda}$$

--Consider a dim-6 potential

$$V \sim -\lambda H^4 + \frac{H^6}{M^2} \qquad \langle H^2 \rangle \sim \lambda M^2$$

If $\lambda \sim 1$, the VEV is not reliable.

Validity of the Effective Field Theory

Ironically, the LEP paradox exists precisely because no large quartic (λ) can be written down with just the MSSM d.o.f !!!

$$W \supset \mu H_u H_d + \frac{1}{2\mu_s}(H_u H_d)^2$$

$$V = \left(|H_u^0|^2 + |H_d^0|^2\right)\left|\mu - \frac{1}{\mu_S} H_u^0 H_d^0\right|^2$$

$$\lambda = \frac{\mu}{\mu_S} \ll 1 \quad (\mu \ll \mu_S)$$

$$\langle H^2 \rangle \sim \lambda M^2 \sim \mu \mu_S$$

Ignored operators?

Ignored superpotential operators:

$$W = \mu H_u H_d + \frac{\omega_1}{2\mu_S}(H_u H_d)^2 + \frac{\omega_2}{3\mu_S^3}(H_u H_d)^3 + \cdots ,$$

higher-order effects are suppressed by $\frac{\mu}{\mu_S}$

Note, the importance of an operator can only be assessed after expanding around the right minimum.

Ignored operators?

Ignored Kahler terms:

$$K \supset H_u^\dagger e^V H_u \left(1 + \frac{1}{\mu_S^2} H_u^\dagger e^V H_u\right) + \ldots$$

higher-order effects are suppressed by $\dfrac{\mu}{\mu_S}$

Nevertheless, leading corrections to

$$\tan\beta = 1 + \mathcal{O}\left(\frac{\mu}{\mu_S}\right), \qquad g_{H_{SM}ZZ}$$

Away from the SUSY-limit

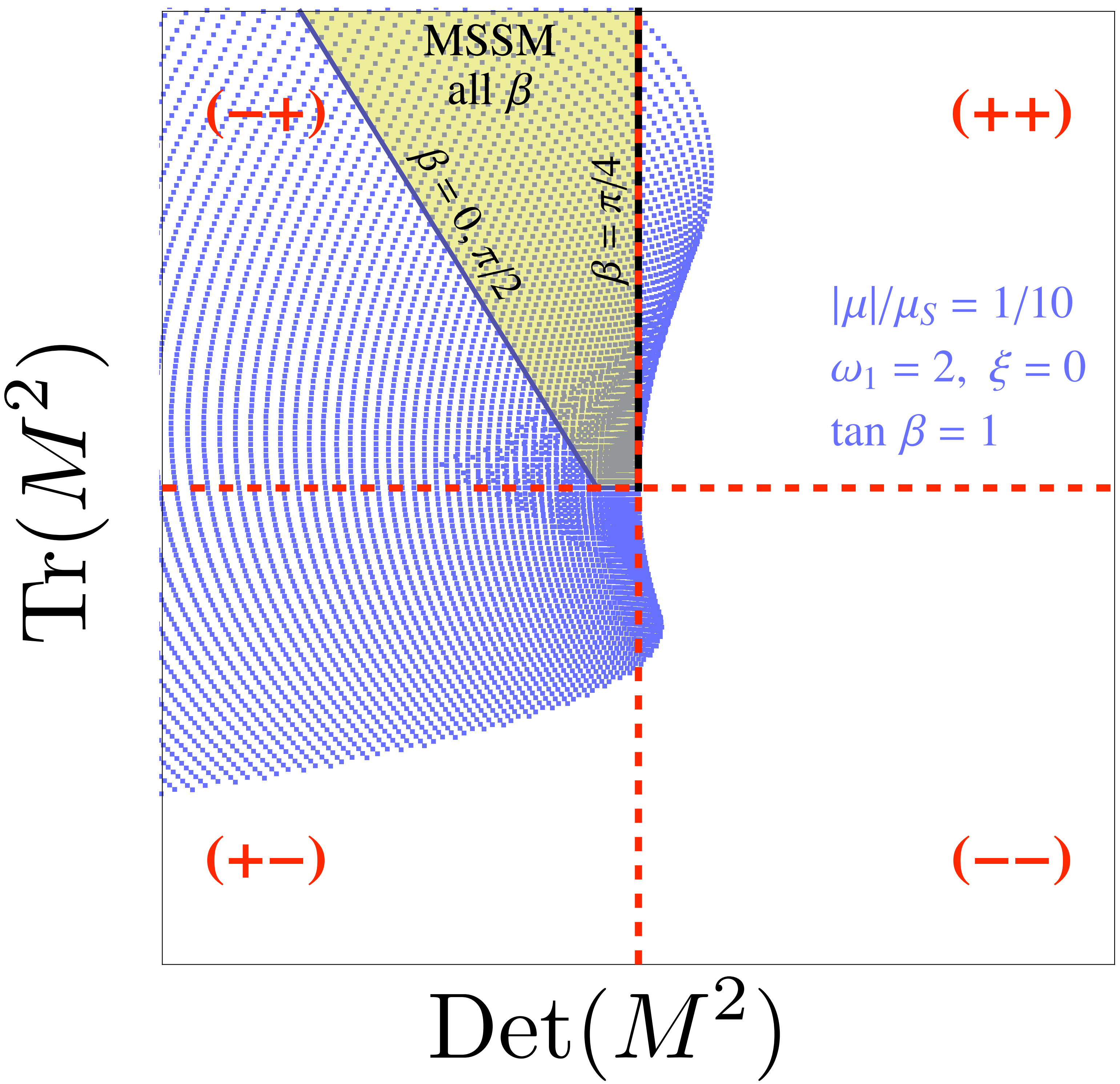
SUSY-breaking is required to lift slepton/squark masses

--sEWSB defined as SUSY is restored

-- Benefit of the EFT: only one new soft-term in the Higgs sector

$$V_{\rm SB} \;=\; m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + \left[b\, H_u H_d - \xi \left(\frac{\omega_1 \mu}{2\mu_s}\right)(H_u H_d)^2 + h.c.\right]$$

Much larger region of EWSB



signs matter,

$$\beta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

$$\tan(\beta) < 0!$$

Away from the SUSY-limit

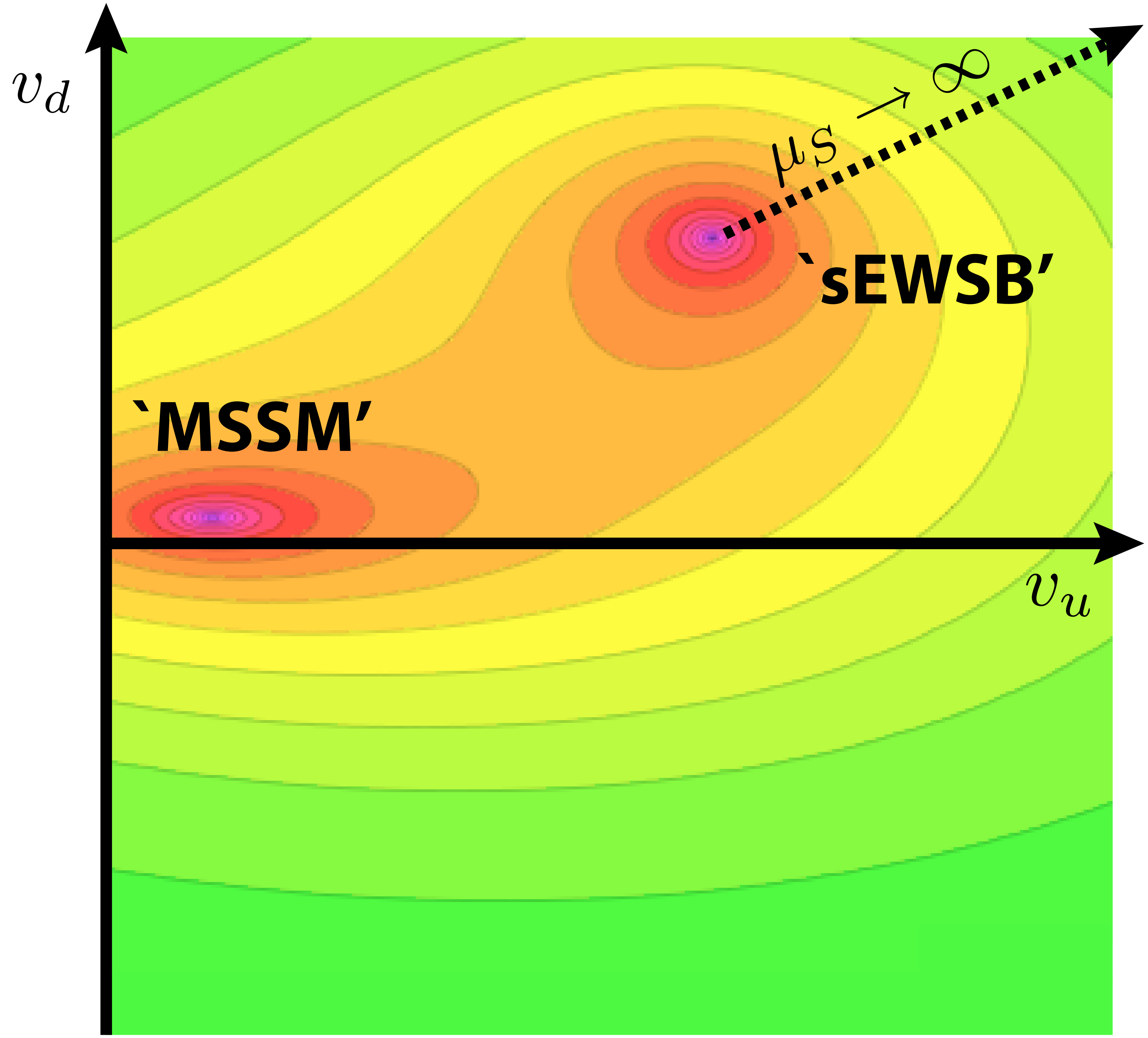
Some tension between making m_{H^0} large, but keeping the EFT under control.

$$2\mu \text{ vs. } v^2 = \mu\mu_S \text{ vs.} \frac{\mu}{\mu_S} \ll 1$$

SUSY-breaking eases this tension

- lifts the masses of $\chi^{\pm}, \chi^0, H^{\pm}$ above LEP bounds
- introduces MSSM-like vacua
- ensures that sEWSB vacua are global minima

Rich Vacuum Structure



Decoupling of sEWSB vacua as new physics becomes massive

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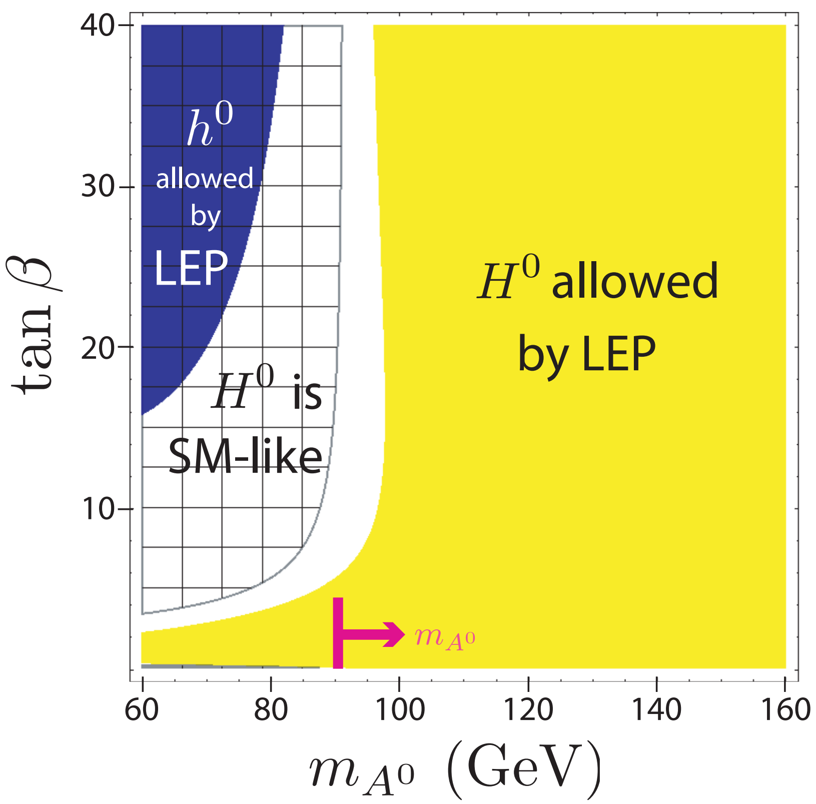
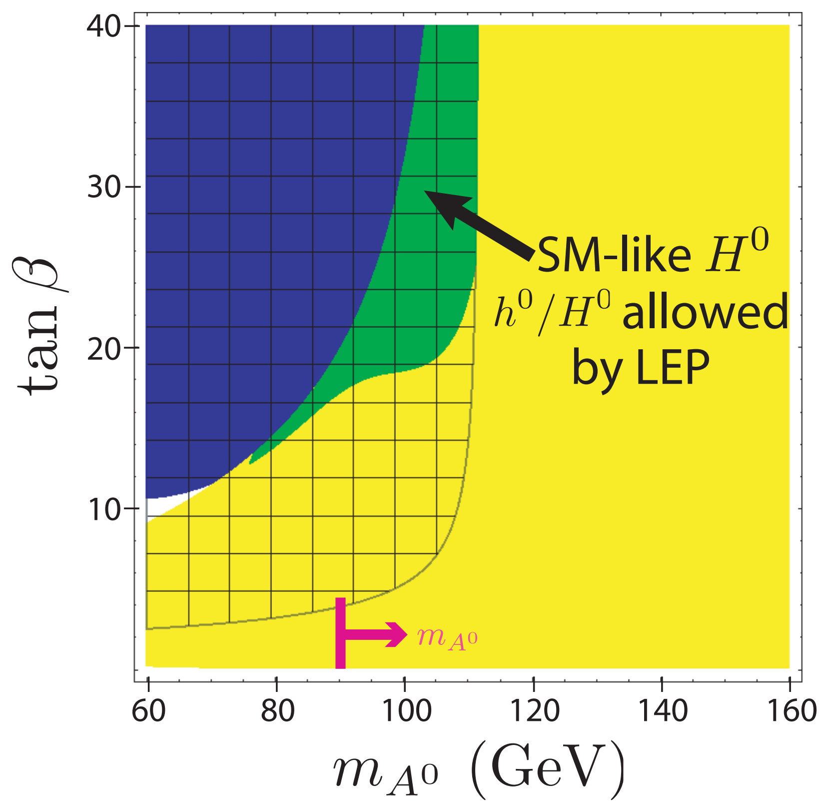
Inverted Hierarchy in the MSSM

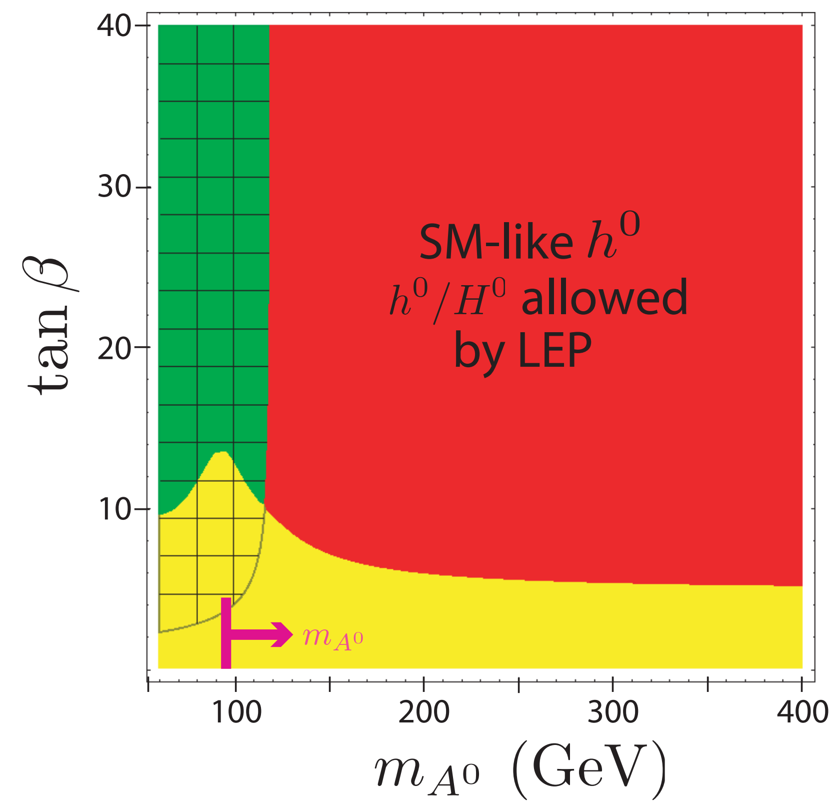
- Inverted Hierarchy: H^0 is SM-like ($m_{h^0} < m_{H^0}$)



$M_{\tilde{t}} \sim m_t$

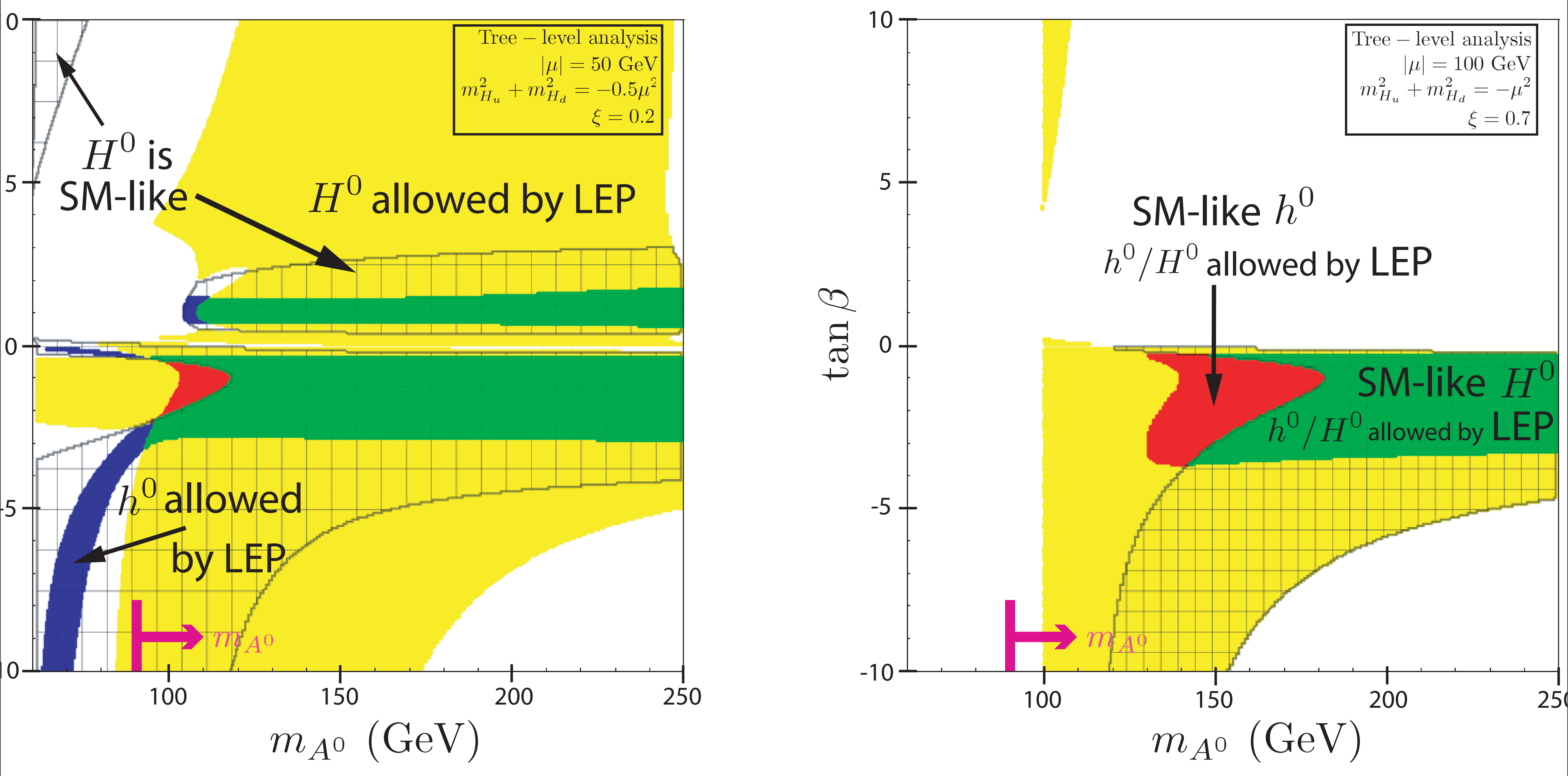


$M_{\tilde{t}} \sim 400$ GeV



$M_{\tilde{t}} \sim 600$ GeV

Inverted Hierarchy in sEWSB vacua



Inverted hierarchy in roughly 'half' of parameter space

Example Inverted Spectra

Point 1

μ	ω	μ/μ_s	b/μ^2	m_u^2/μ^2	$m_{H_d}^2/\mu^2$	ξ	M_1/μ	M_2/μ
-60	1	0.11	-2.2	-1.7	-0.60	0.20	1.5	1.7

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g^2_{H^0ZZ}/g^2_{h_{\rm SM}ZZ}$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
0.47	-1.3	120	150	0.98	100	120	110	90

Point 2

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-150	2	0.14	-1.1	-0.99	-0.51	0.20	0.36	0.57

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Extreme Inverted Spectra

μ	ω	μ/μ_s	b/μ^2	m_u^2/μ^2	$m_{H_d}^2/\mu^2$	ξ	M_1/μ	M_2/μ
-70	3.5	0.19	1.95	-0.45	-0.47	0.70	-1.0	.86

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g_{H^0ZZ}^2/g_{h_{\rm SM}ZZ}^2$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
1.8	0.99	100	350	1	300	90	100	48

Orientation at low $\tan\beta$

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- up-type couplings:

$$\frac{h^0 t\bar{t}}{h_{SM} t\bar{t}} = s_{\beta-\alpha} + \cot_\beta c_{\beta-\alpha} \to 1 \qquad \frac{H^0 t\bar{t}}{h_{SM} t\bar{t}} = c_{\beta-\alpha} - \cot_\beta s_{\beta-\alpha} \to 1$$

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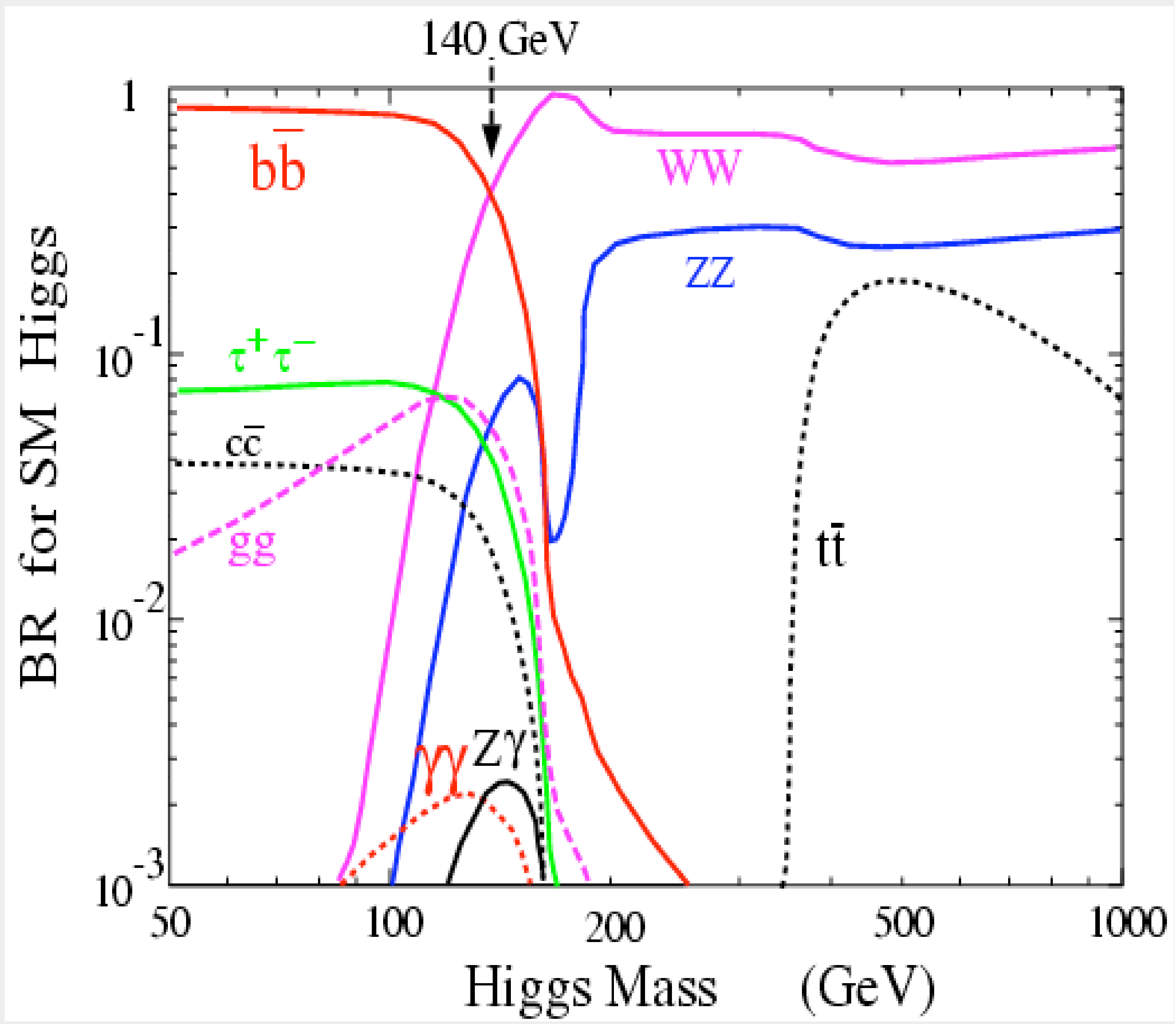
- gluon fusion unchanged, important contrib. to $h^0 \to \gamma\gamma$

$$\frac{h^0 t\bar{t}}{h_{SM} t\bar{t}} = s_{\beta-\alpha} + \cot_\beta c_{\beta-\alpha} \to 1 \qquad \frac{H^0 t\bar{t}}{h_{SM} t\bar{t}} = c_{\beta-\alpha} - \cot_\beta s_{\beta-\alpha} \to 1$$

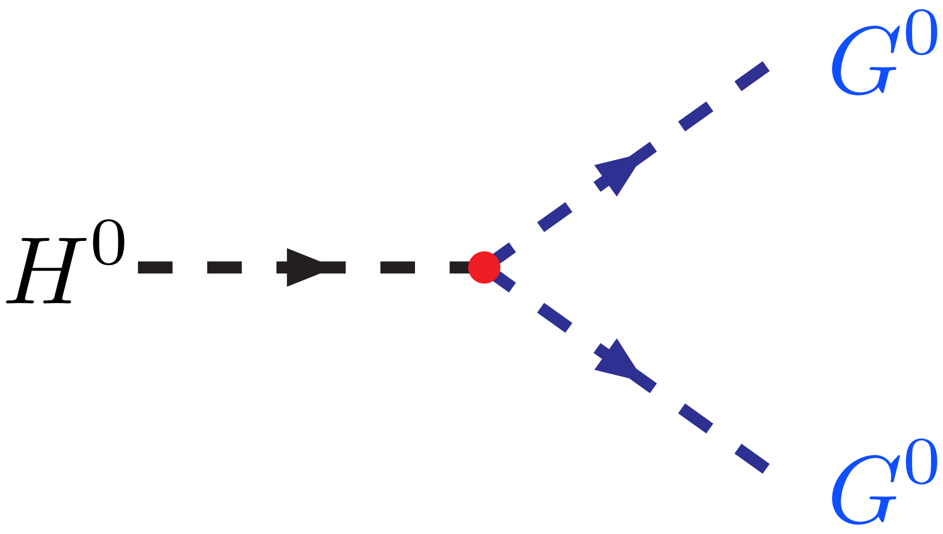
Enhanced Scalar Decays



Low mass, $H \rightarrow b\bar{b}$ dominates

High mass, $H \rightarrow W^+W^-(ZZ)$ dominates

Enhanced Scalar Decays



$$\lambda v \sim \frac{m_{H^0}^2}{v}$$

$$\Gamma\left(H^0 \to ZZ\right) \sim \frac{m_{H^0}^3}{v^2}$$

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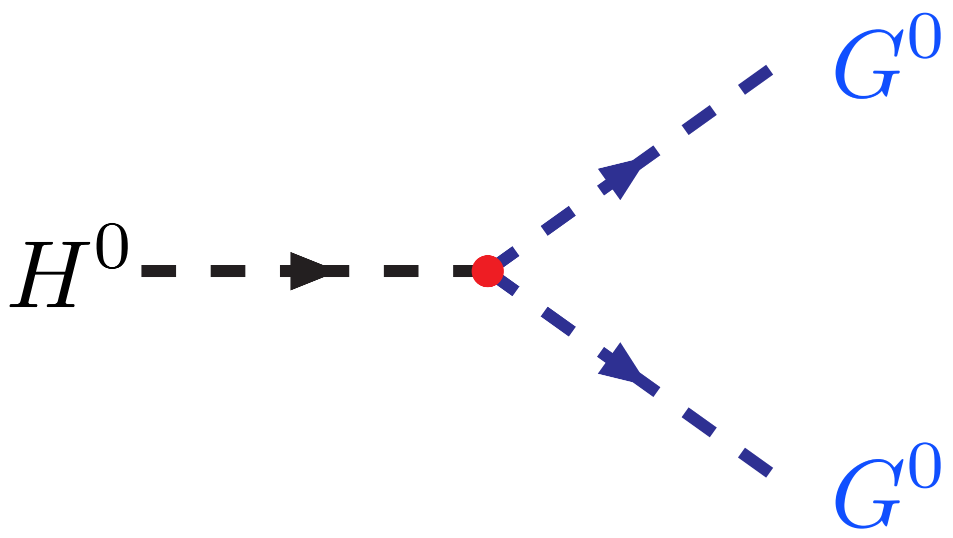

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- Consider

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g^2_{H^0ZZ}/g^2_{h_{\rm SM}ZZ}$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
1.8	0.99	100	350	1	300	90	100	48

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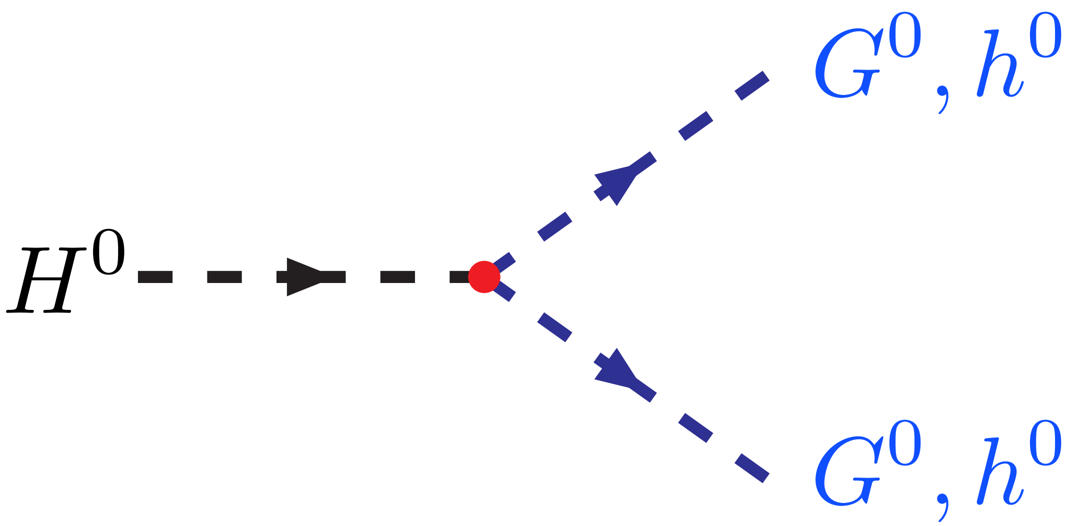

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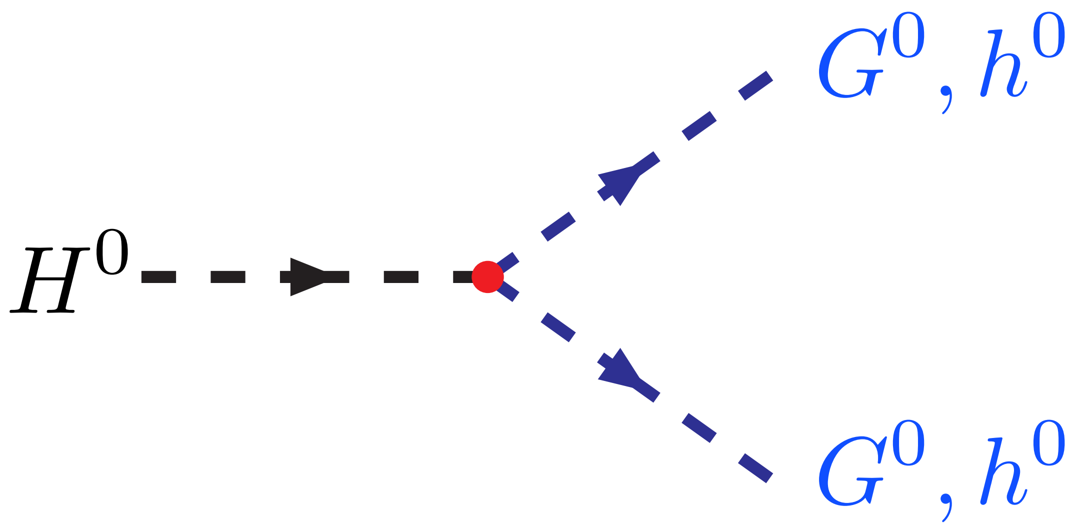

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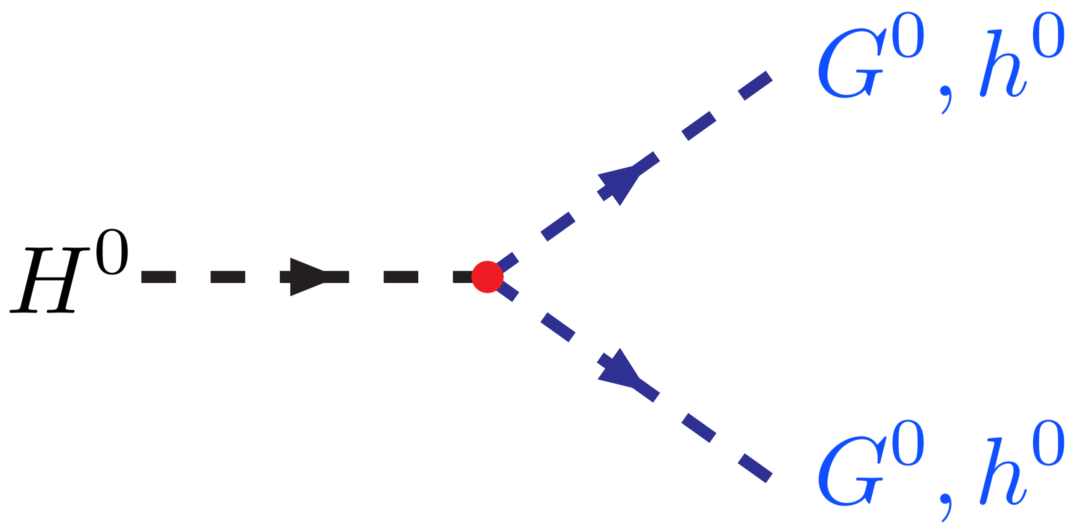
- $$\frac{Br\left(H^0 \to 2h^0, H^\pm\right)}{Br\left(H^0 \to VV\right)} \sim \frac{1}{5}$$

Enhanced Scalar Decays



$$\lambda v \sim \frac{m_{H^0}^2}{v}$$

$$\Gamma\left(H^0 \to h^0 h^0\right) \sim \frac{m_{H^0}^3}{v^2}$$

Toy model:

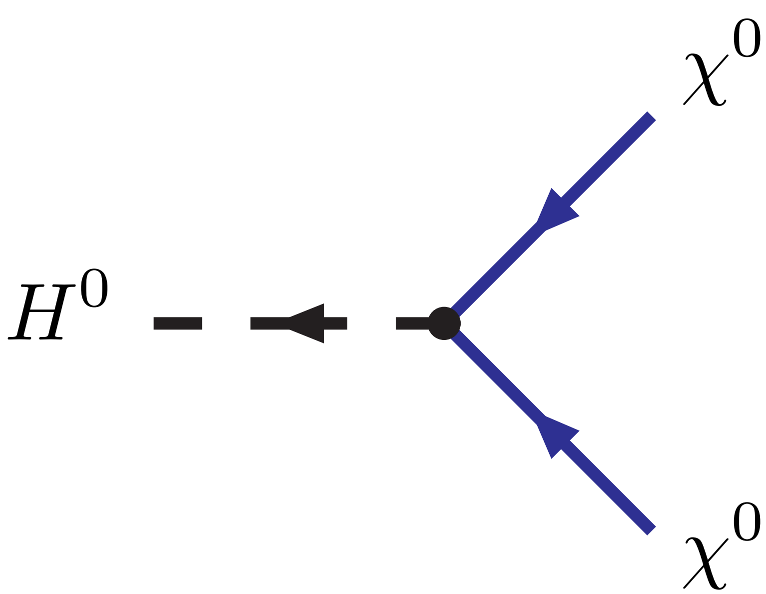
$$\mathcal{L} \supset -m_H^2 |H|^2 + \lambda |H|^4 + \lambda |H|^2 |S|^2 - m_S^2 |S|^2$$

cancel to 20% in our model

Inverted Phenomenology

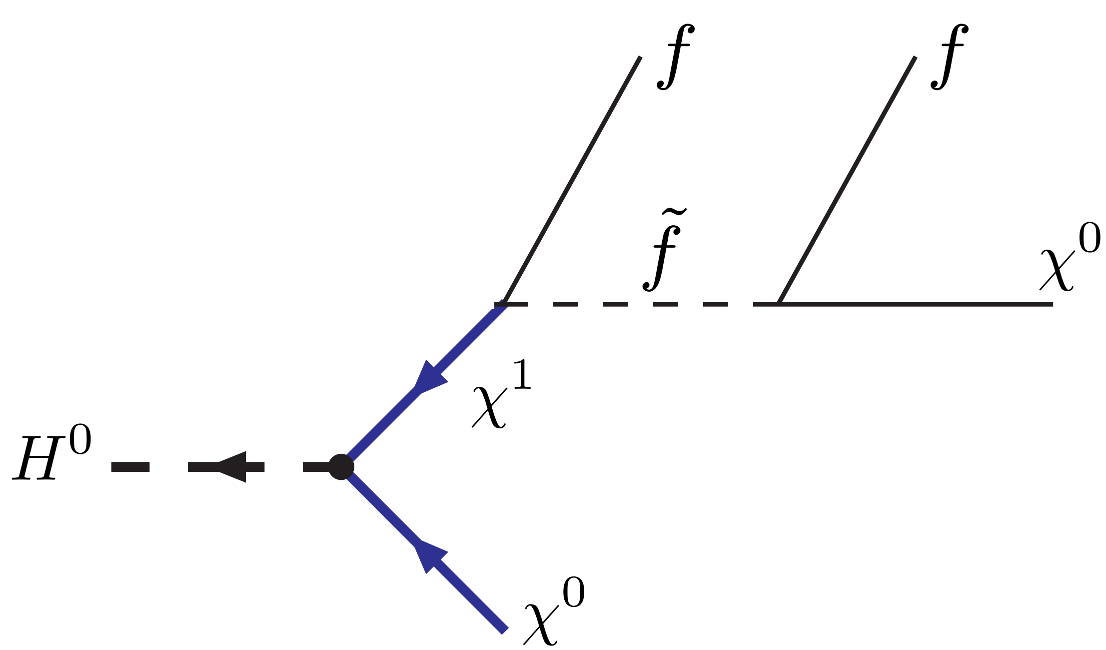
Higgs to SUSY decay modes

Haber, Dicus,Dress & Tata; Gunion & Haber, ...



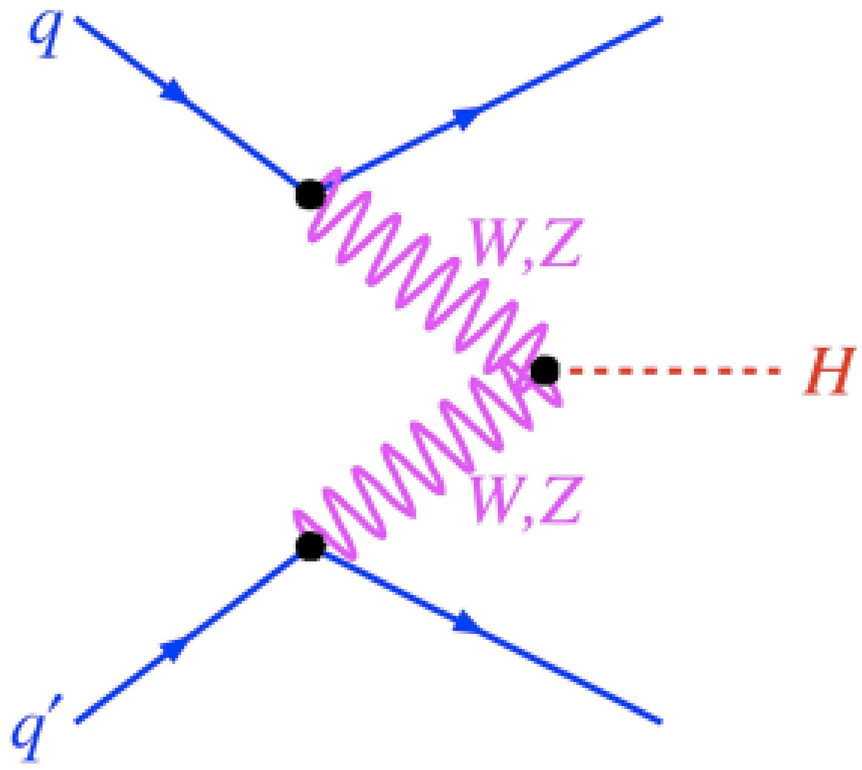
$$\Gamma \propto g^2 m_H$$

$$(\Gamma \propto y_b^2 m_H)$$

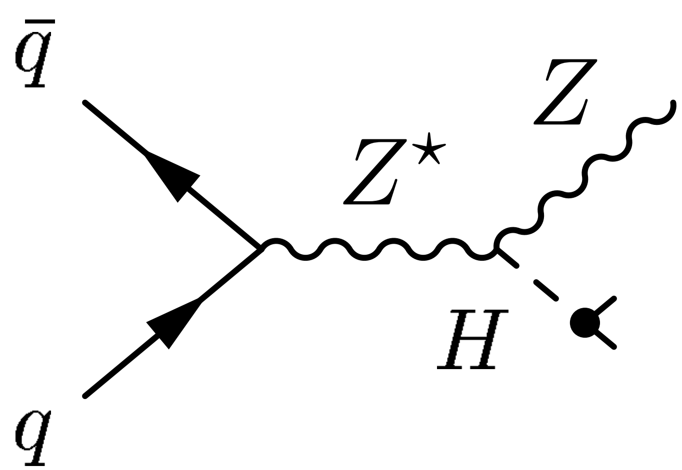


Invisible Higgs Decays

Higgs to SUSY decay modes



Eboli, Zeppenfeld



Godbole et al.,
Davoudiasl, Han, Logan

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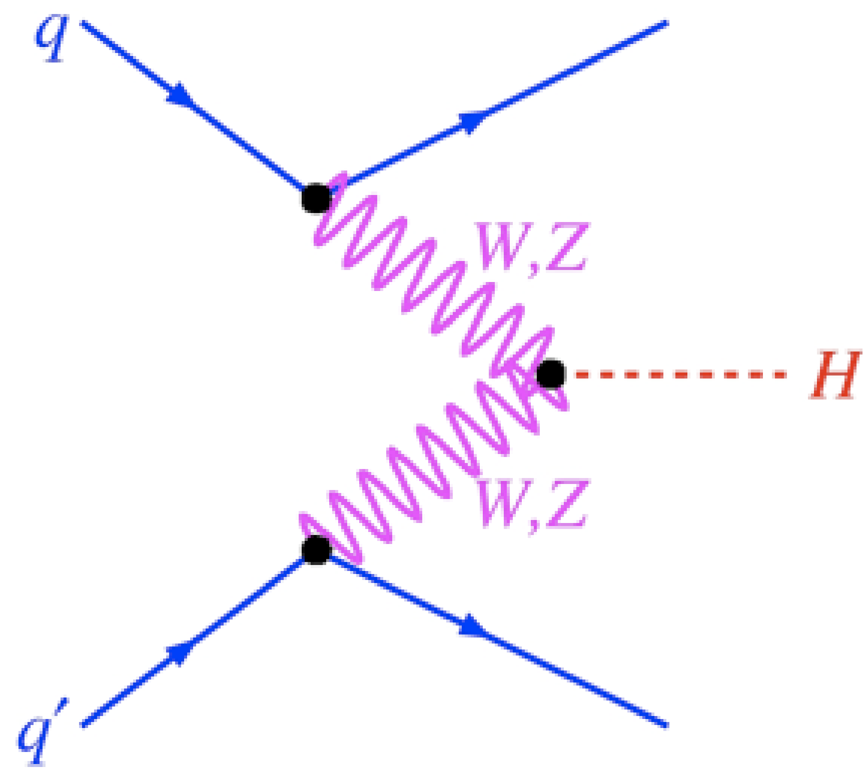


Eboli, Zeppenfeld

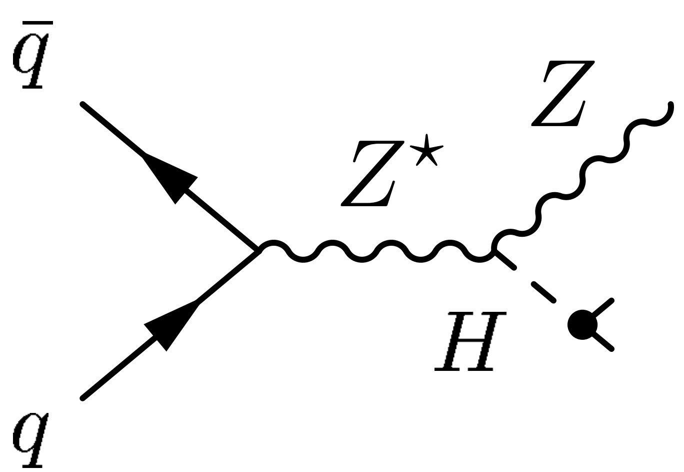
LHC:

M_H (GeV)	110	120	130	150	200	300	400
10 fb^{-1}	12.6%	13.0%	13.3%	14.1%	16.3%	22.3%	30.8%
100 fb^{-1}	4.8%	4.9%	5.1%	5.3%	6.2%	8.5%	11.7%

Invisible Higgs Decays

Higgs to SUSY decay modes

Godbole et al.,
Davoudiasl, Han, Logan



LHC:

$\not{p}_T$ cut	$m_h = 120$ GeV S/B	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (10 fb^{-1})	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 140$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 160$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)	7.1 (6.2)	5.2 (4.5)
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

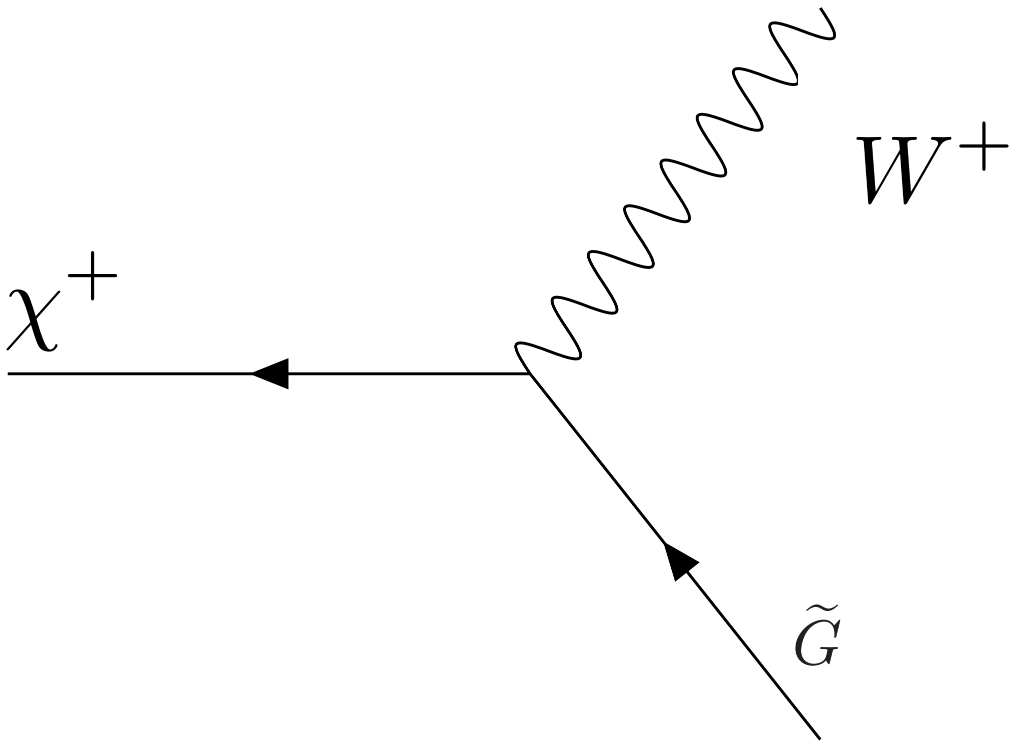
Chargino NLSP?

Chargino NLSP?

Kribs, Martin, Roy

μ	ω	μ/μ_s	b/μ^2	m_u^2/μ^2	$m_{H_d}^2/\mu^2$	ξ	M_1/μ	M_2/μ
-70	1	0.11	-1.6	-1.7	.22	0.20	1.5	1.7

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g^2_{H^0 ZZ}/g^2_{h_{\rm SM} ZZ}$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
0.34	-1.8	120	140	0.82	110	125	100	110



Every SUSY event has

$$W^+W^- + \text{ MET}$$

Chargino decay may be prompt, displaced, or outside the detector.

Inverted Phenomenology

Charged Higgs constraints

-- direct constraints from LEP, $m_{H^+} > 80 \text{ GeV}$

-- indirect constraints from B factories

$$b \to s\gamma \quad : \quad m_{H^+} > 300 \text{ GeV}$$

vanishes in the SUSY-limit

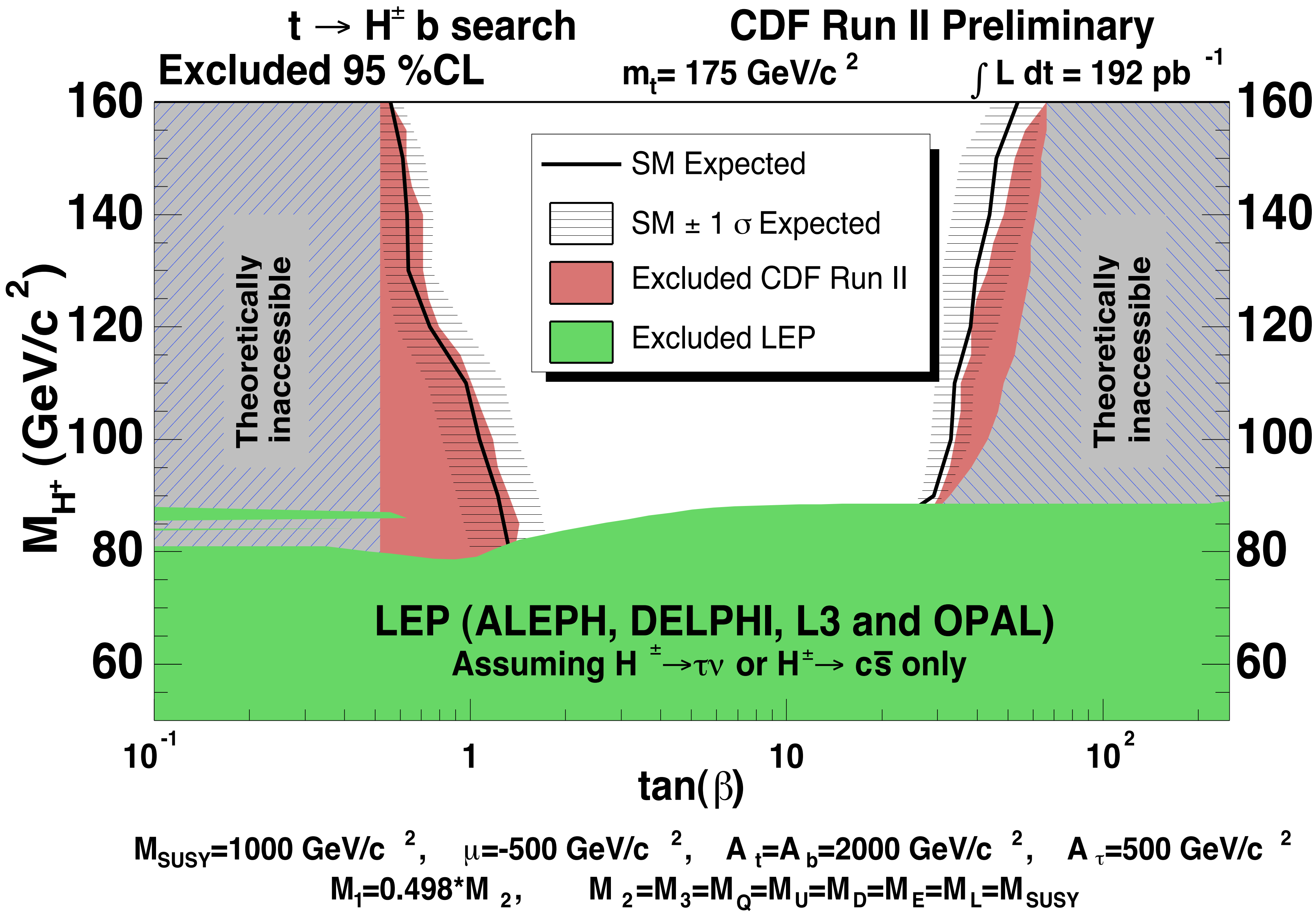
Ferrara & Remiddi, Barbieri & Giudice

-- direct constraints from Tevatron, when $t \to H^+ b$

Inverted Phenomenology

Charged Higgs constraints

-- direct constraints from Tevatron, when $t \to H^+ b$



Inverted Phenomenology

Charged Higgs constraints

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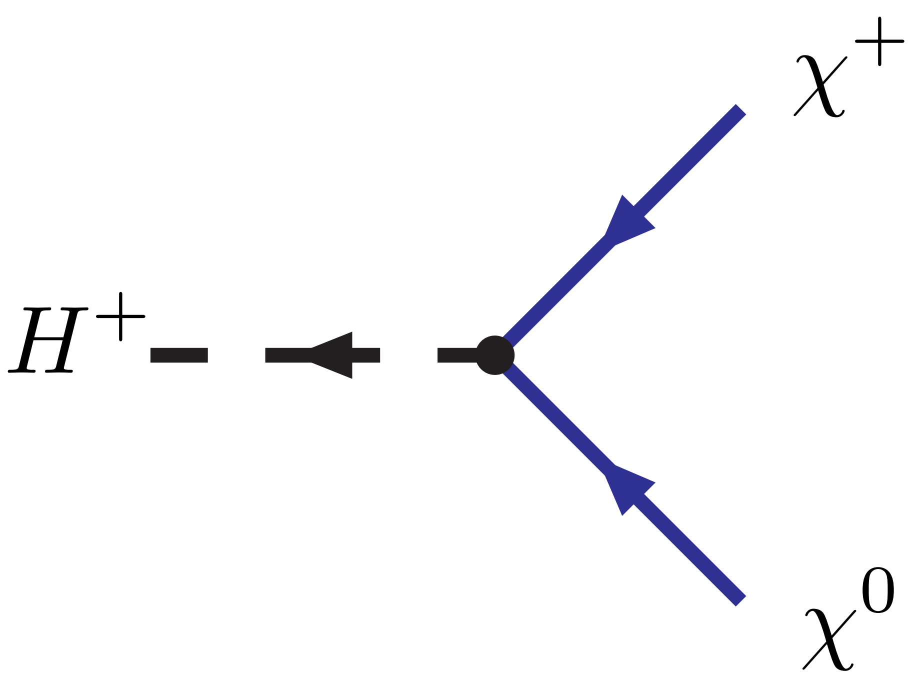


$$\Gamma \propto g^2 m_H$$

$$(\Gamma \propto y_b^2 m_H)$$

--unexplored top decay channel!

Conclusions

- Post-LEP, it is worth reconsidering what the most likely BSM Higgs sector looks like:

$h^0 \rightarrow 2a \rightarrow 4b$ $\quad$ $m_{h^0} < m_{H^0}, H^0$ SM-like

- Supersymmetric EWSB is a qualitatively new starting point---EFT approach is very powerful!

Easy to UV complete into a theory with $W \supset \lambda S H_u H_d$

- Light Higgs -> enhanced scalar decays, Light charginos, charged Higgs = new phenomenology!

Rich Vacuum Structure---cosmological applications?

Uniquely Identifiable?

- supplements

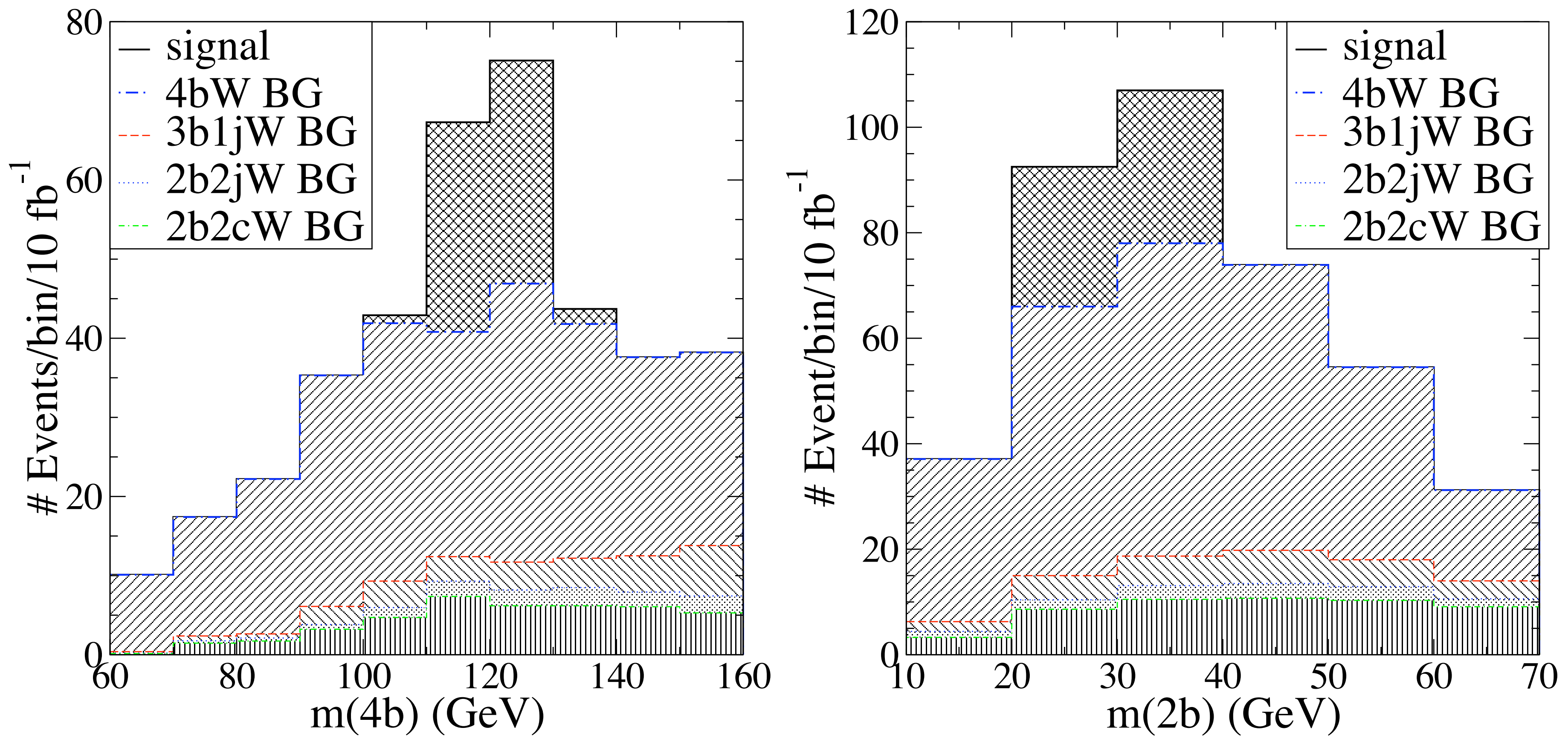


Figure 5: Higgs signal (double-hatched) on top of the sum of the backgrounds at the LHC in the $4b$ decay channel together with a leptonically decaying W. The invariant mass of four (left) and two (right) b-jets are shown. Constraints of $60\,\text{GeV} < m(4b) < 160\,\text{GeV}$ and $10\,\text{GeV} < m(2b) < 70\,\text{GeV}$ are implemented in both plots. $C_{4b}^2 = 0.50$, $m_h = 120\,\text{GeV}$ and $m_a = 30\,\text{GeV}$ are understood. From bottom to top, the background histograms indicate the accumulative sum of $2b2cW$, $2b2cW + 2b2jW$, $2b2cW + 2b2jW + 3b1jW$, and $2b2cW + 2b2jW + 3b1jW + 4bW$, respectively.

CP conservation:

$$b/|\mu|^2 \geq 0 \text{ or } \xi\mu^2 > 0,$$

No Charge-Breaking

$$\left\{4m_{H_d}^2 + v^2\left(g^2 + g'^2 c_{2\beta}\right) + 4|\mu|^2\left(\rho s_{2\beta} - 1\right)^2\right\} \geq 0$$

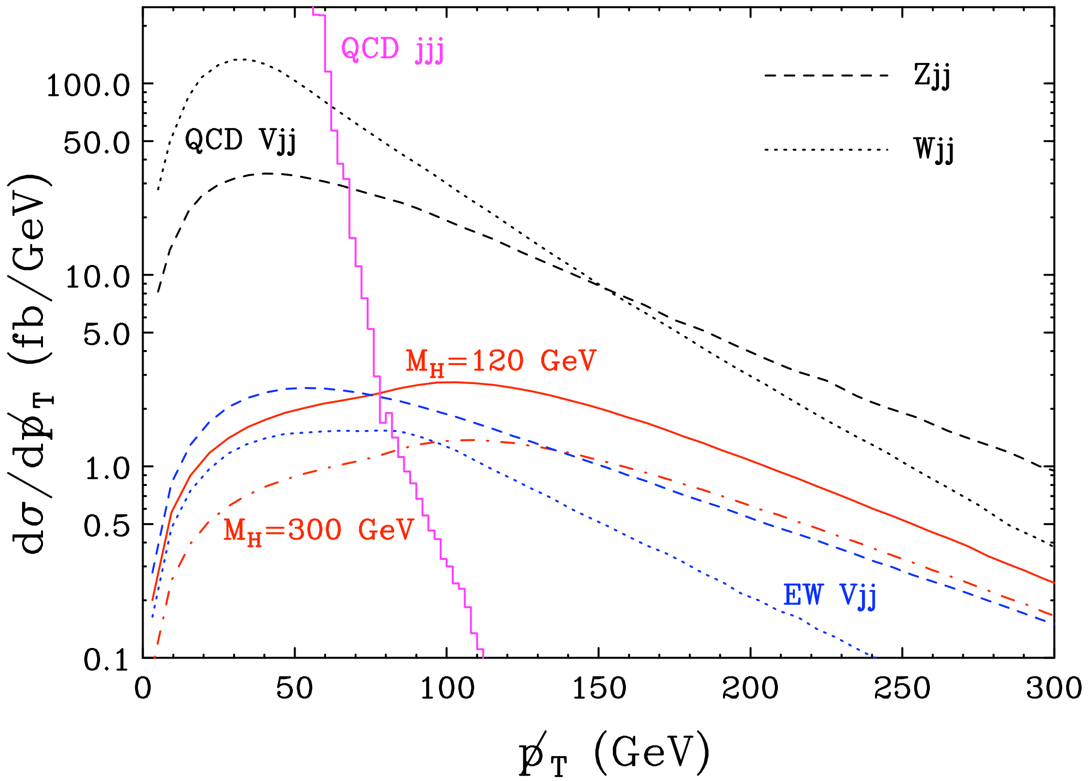


FIG. 1. Missing transverse momentum spectra within the cuts (1) and (3). Results are shown separately for the EW Zjj (blue dashed line) and Wjj (blue dotted line) backgrounds, as well as the QCD processes Zjj (black dashed line), Wjj (black dotted line), and jjj (magenta histogram) production. We exhibit the invisible Higgs contribution for $M_H = 120$ (red solid line) and 300 GeV (red dot-dashed line).

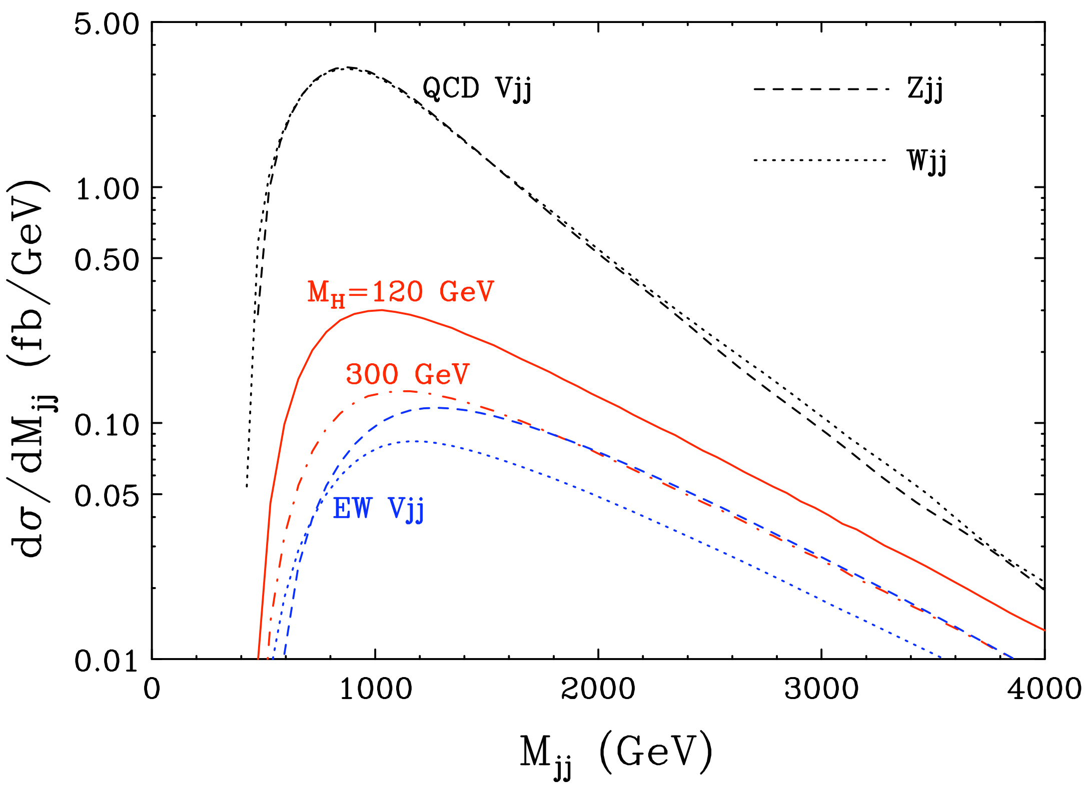


FIG. 2. Dijet invariant mass distributions when applying the cuts of Eqs. (1,2). The lines follow

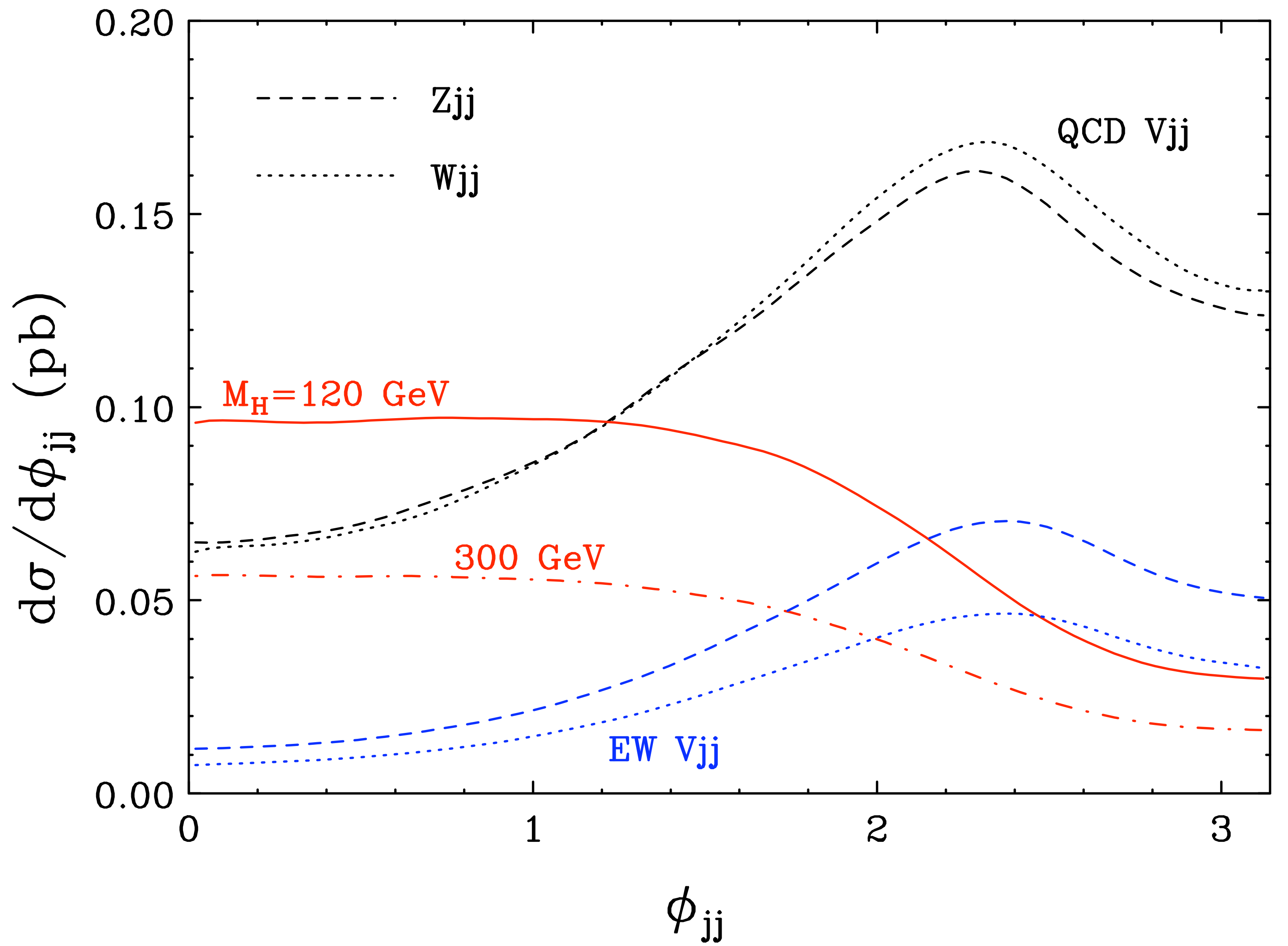


FIG. 3. Distributions of the azimuthal angle separation between the two tagging jets for the various background processes and the Higgs signal at $M_H = 120$ and 300 GeV. Results are shown after applying the cuts (1-3) and including the effect of a central jet veto with the survival probabilities of Table I. The lines follow the same convention as in Fig. 1.

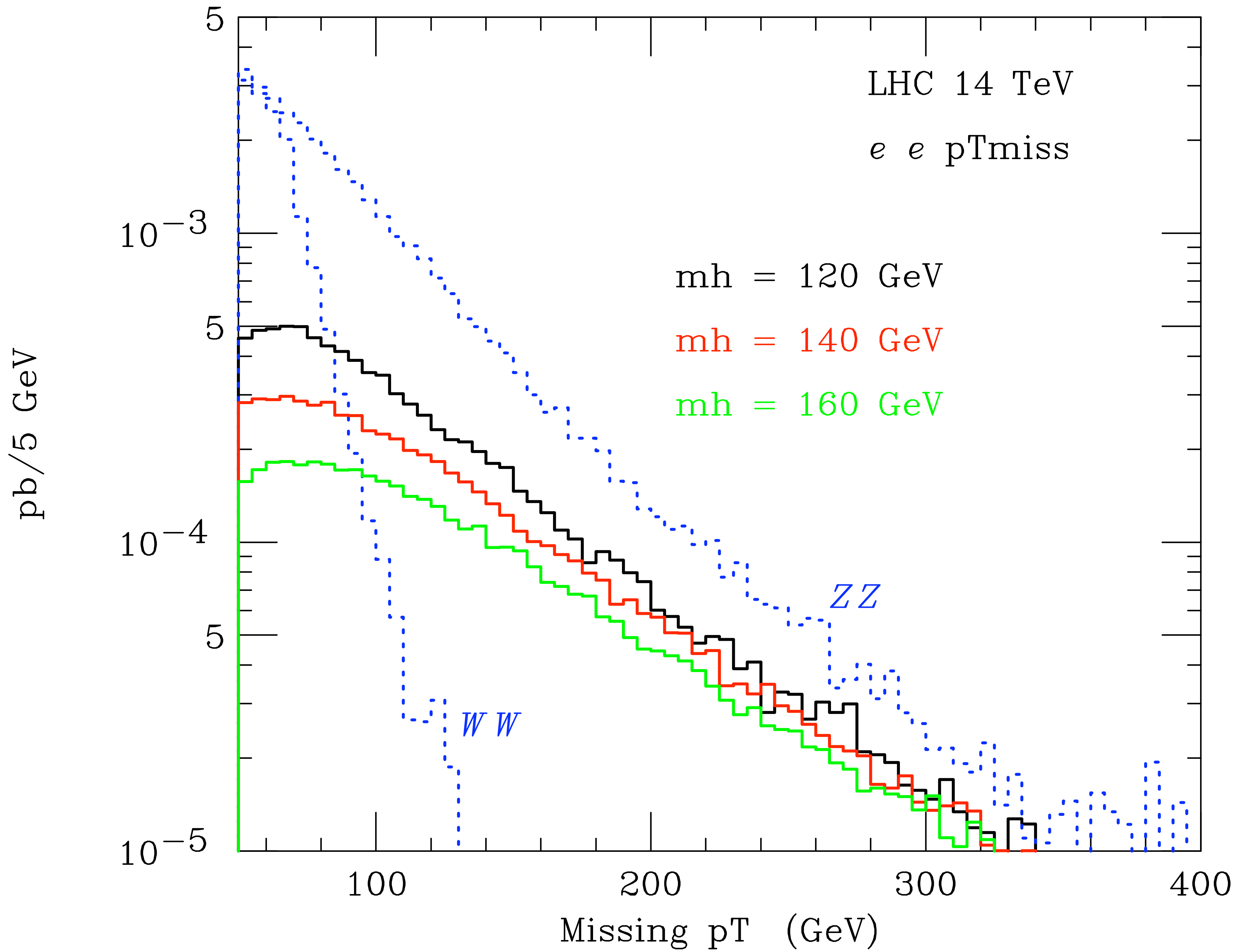
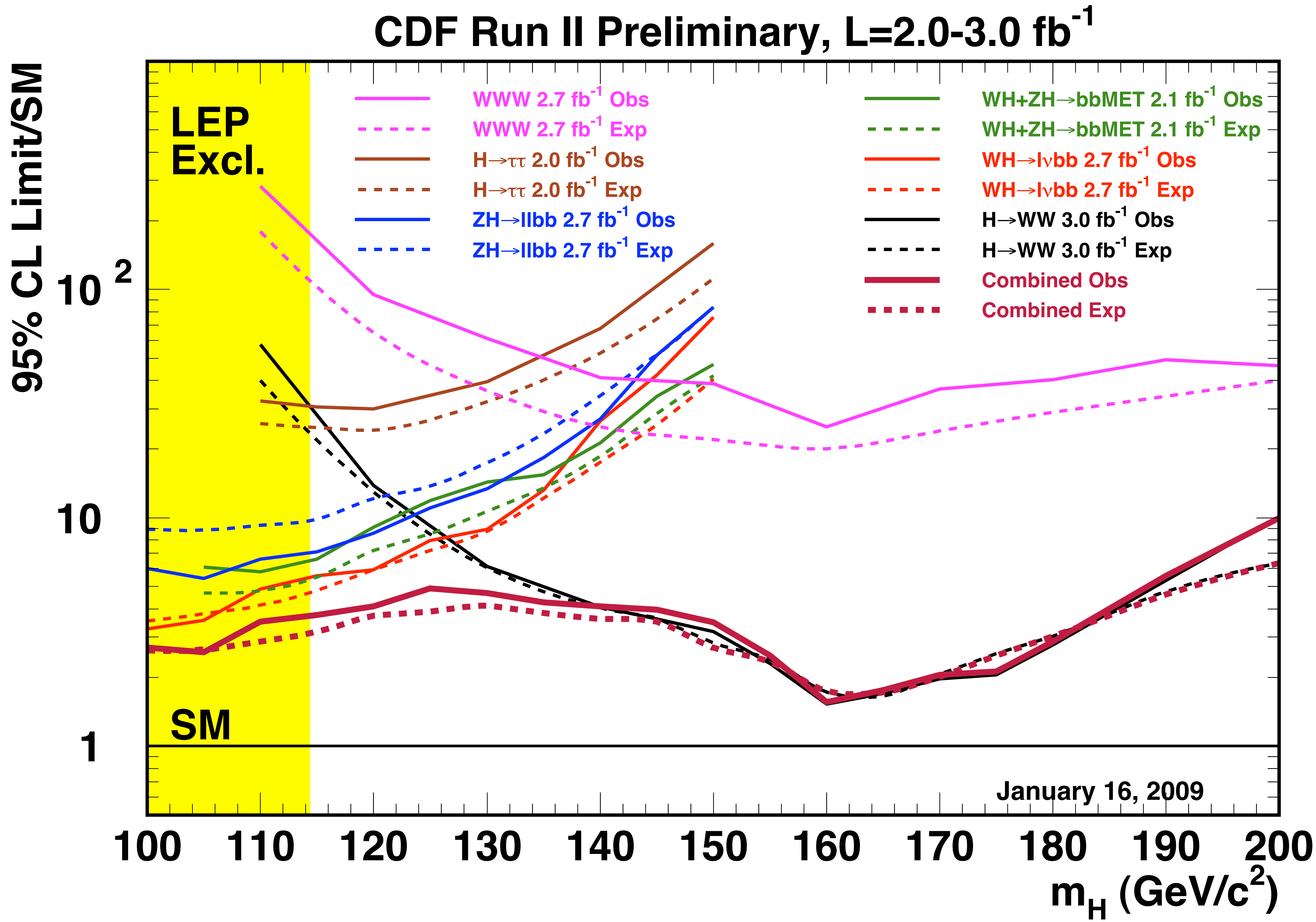


FIG. 1: Missing p_T distribution for $Z(\to e^+e^-) + h_{inv}$ signal (solid lines, with $m_h = 120$, 140 and 160 GeV top to bottom) and backgrounds from WW and ZZ (dotted lines) at the LHC, after applying the cuts in Eqs. (3), (5) and (6).

Just CDF bounds



Minimization Relations

$$
\begin{aligned}
s_{2\beta} &= \frac{2b - 4|\mu|^2\rho(\rho s_{2\beta} - 1)}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2(\rho s_{2\beta} - 1)^2 - 2\xi\mu^2\rho} \ , \\
m_Z^2 &= \frac{m_{H_u}^2 - m_{H_d}^2}{c_{2\beta}} - \left[m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2(\rho s_{2\beta} - 1)^2\right] \ , \\
v^2 &\equiv \rho\left(\frac{2\mu\mu_S}{\omega_1}\right) \ .
\end{aligned}
$$

Near SUSY limit

$$V \approx (m_{H_u}^2 + m_{H_d}^2 + 2b)\frac{v^2}{2} \ , \qquad \text{(small SUSY breaking)}$$

$$\rho_\epsilon = \frac{\frac{1}{2}\xi \pm 2}{3}\left\{1+\epsilon\sqrt{1-\frac{3}{(\frac{1}{2}\xi\pm 2)^2}\left(1+\frac{m_{H_u}^2+m_{H_d}^2}{2\mu^2}\mp\frac{b}{\mu^2}\right)}\right\},$$

$$\delta\beta = \pm\frac{m_{H_d}^2-m_{H_u}^2}{2\left(m_Z^2+m_{H_u}^2+m_{H_d}^2+2\mu^2(1\mp\rho_\epsilon)^2\right)},$$

$$\begin{aligned}
m_{A^0}^2 &= 4(\pm 1+\xi)\rho\mu^2 \pm 2b \ + \mathcal{O}(\delta\beta^2),\\
m_{H^0}^2 &= \frac{1}{2}\left[m_Z^2+m_{A^0}^2+8\mu^2\rho(\rho\mp 1-\xi/2)+|D|\right]+\mathcal{O}(\delta\beta^2),\\
m_{h^0}^2 &= \frac{1}{2}\left[m_Z^2+m_{A^0}^2+8\mu^2\rho(\rho\mp 1-\xi/2)-|D|\right]+\mathcal{O}(\delta\beta^2),\\
D &\equiv m_Z^2+m_{A^0}^2-8\mu^2\rho(2\rho\mp 1).
\end{aligned}$$

$$c_{\beta-\alpha}^2 = \begin{cases} 0+\mathcal{O}(\delta\beta^2) & D>0\\ 1+\mathcal{O}(\delta\beta^2) & D<0 \end{cases}.$$

$$m_{H^+}^2 = \begin{cases} m_{H^0}^2 + (m_W^2 - m_Z^2) + \mathcal{O}(\delta\beta^2) & D > 0 \\ m_{h^0}^2 + (m_W^2 - m_Z^2) + \mathcal{O}(\delta\beta^2) & D < 0 \end{cases} .$$