Light MSSM Higgs boson scenario

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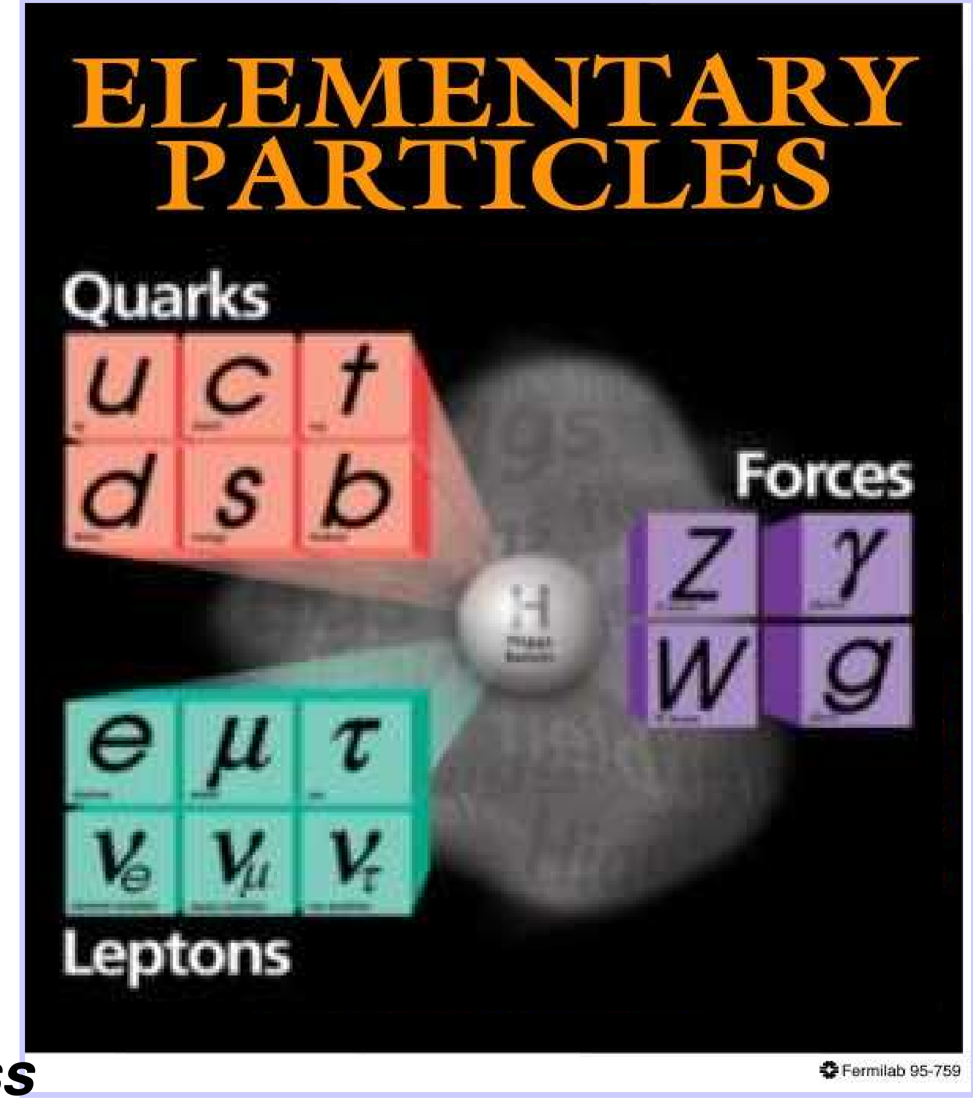
Short Summary

- The MSSM scenario with the CP-even Higgs boson as light as ~60 GeV (and above) is not excluded by LEP2 contrary to common belief
- The MSSM parameter space corresponding to this Light higgs scenario (LHS) is generic
- The entire parameter space corresponding to LHS can be covered by LHC

The present status of the SM

- Based on $SU(3) \times SU(2)_L \times U(1)_Y$ gauge symmetry spontaneously broken down to $SU(3) \times U(1)_e$:
- Matter: 3 generations of quarks and leptons
- One of the central role is played by Higgs field
  - *interacts with all fields*
  - *develops condensate*
  - *W,Z bosons, lepton and quarks and Higgs field itself acquires mass*



Higgs boson is the most wanted particle!

The present Higgs mass limit is 114.4 GeV from LEP2 e^+e^- data

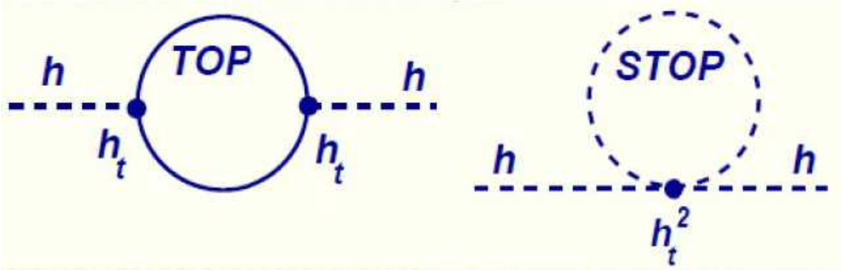
Why Supersymmetry is so attractive?

- relates bosons and fermions

$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle \quad \textbf{AND} \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

- extends Poincaré algebra to super-Poincaré algebra with the most general set of space-time symmetries

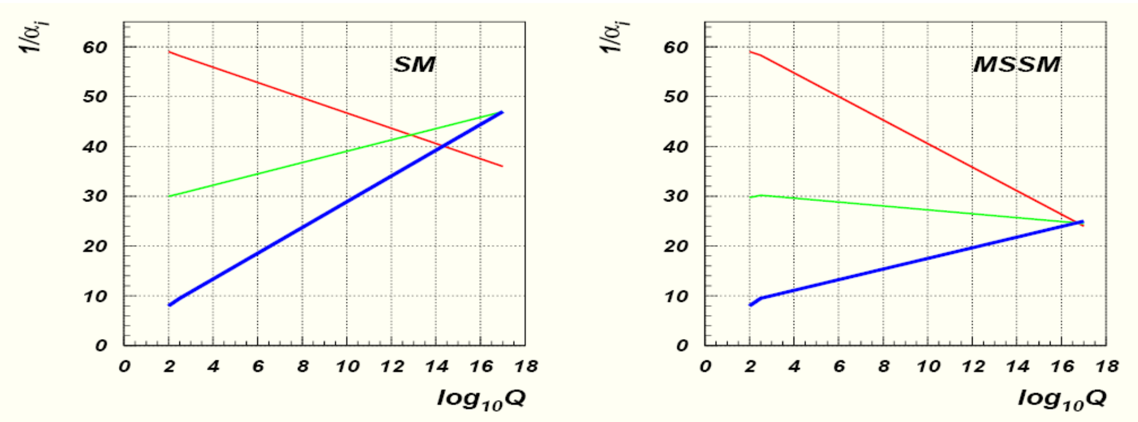
➡ *solves fine-tuning problem of SM*



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$

➡ *provides*

gauge coupling unification



➡ *LSP is stable (R-parity):*

perfect DM candidate

➡ *allows to introduce fermions into string theories*

MSSM HIGGS sector

- **two Higgs complex-doublet**
  - ***provides masses to both up- and down- quarks***
  - ***ensures anomaly cancellation***

$$\Phi_d = (\Phi_d^0, \Phi_d^-) \text{ and } \Phi_u = (\Phi_u^+, \Phi_u^0), \quad \langle\Phi_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle\Phi_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_u \end{pmatrix},$$

where $\sqrt{v_d^2 + v_u^2} = 2M_W/g = v(\ 246 \text{ GeV}), \quad v_u/v_d = \tan\beta$

- **8 degrees of freedom**
  - ***3 absorbed into longitudinal components of the W and Z***
  - ***5 remains:***

$$\begin{aligned} h &= -(\sqrt{2}\mathrm{Re}\ \Phi_d^0 - v_d)\sin\alpha + (\sqrt{2}\mathrm{Re}\ \Phi_u^0 - v_u)\cos\alpha \\ H &= \ (\sqrt{2}\mathrm{Re}\ \Phi_d^0 - v_d)\cos\alpha + (\sqrt{2}\mathrm{Re}\ \Phi_u^0 - v_u)\sin\alpha \\ A &= \sqrt{2}(\mathrm{Im}\ \Phi_d^0 \sin\beta + \mathrm{Im}\ \Phi_u^0 \cos\beta), \\ H^\pm &= \Phi_d^\pm \sin\beta + \Phi_u^\pm \cos\beta \end{aligned}$$

α is (h, H) mixing angle; $\tan\beta$ and M_A define the tree-level Higgs sector

$$M_{H^\pm} = \sqrt{M_A^2 + M_W^2}$$

$$M_{h,H}^2 = \frac{1}{2}\left[(M_A^2 + M_Z^2) \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right], \quad M_h < M_Z$$

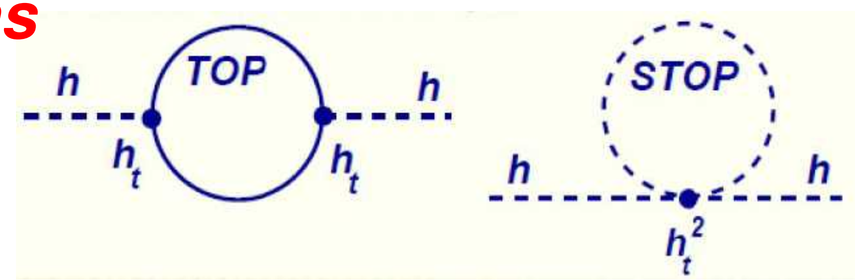
"Little" Fine Tuning in MSSM

- MSSM has a "little problem": $M_h < M_Z$ at the tree-level!
- Solution to obey $M_h > 114.4$ GeV LEP2 limit:

  SUSY scale $\gtrsim$ 1 TeV

  top-stop radiative corrections

$$\delta M_h \propto m_t^4 \log\left(\frac{M_{SUSY}}{m_t}\right)$$

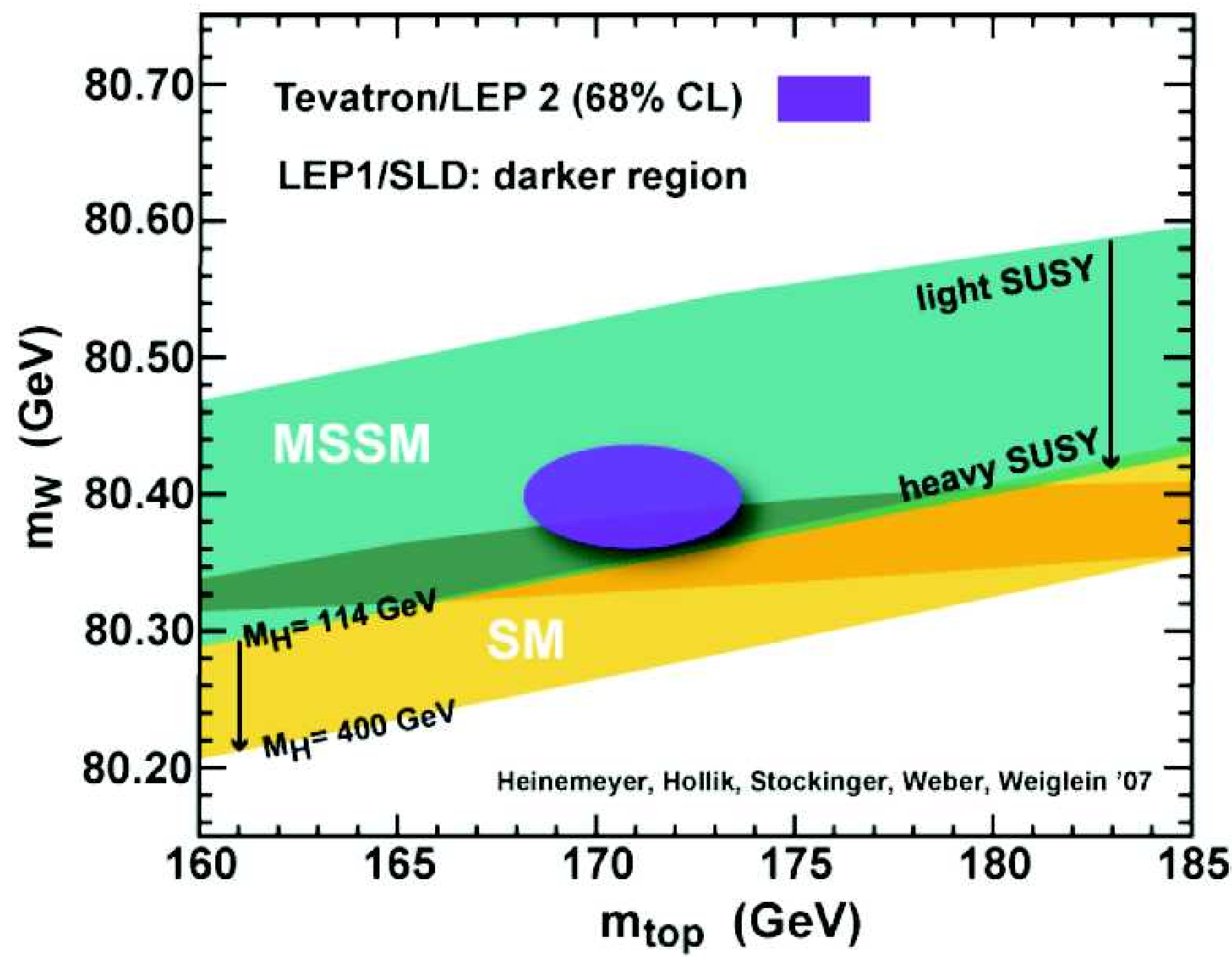


- the price: ~ 1% of fine-tuning

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

- is there other way to avoid LEP2 Higgs bound?

Higgs (if there is) prefers to be non-SM like!



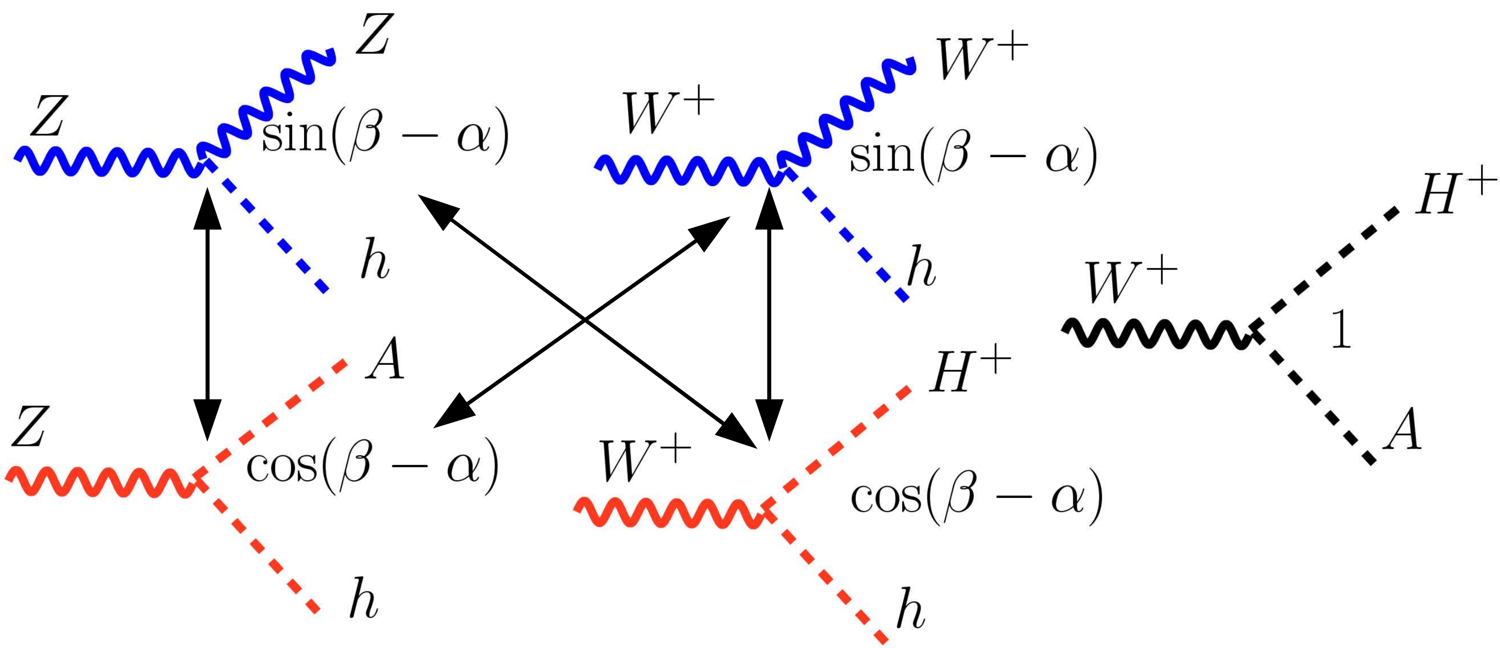
MSSM Higgs Interactions with vector bosons

$$\mathcal{L}_{H_iVV} = g\,M_W\left(W^+_\mu W^{-\mu} + \frac{1}{2c_W^2}Z_\mu Z^\mu\right) g_{H_iVV}\,H_i$$

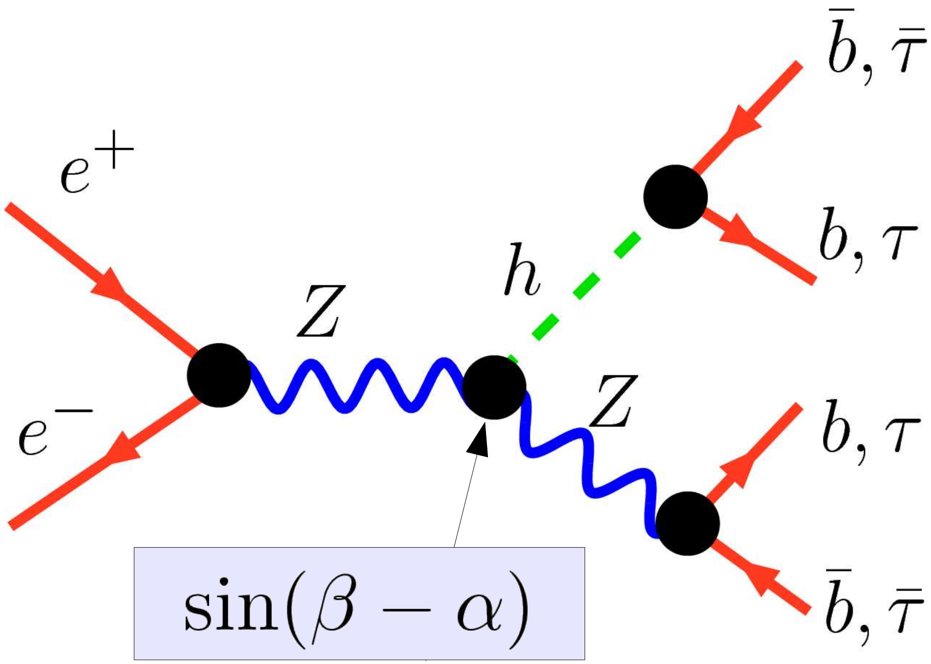
$$\mathcal{L}_{AH_iZ} = \frac{g}{4c_W} g_{AH_iZ}\,Z^\mu(H_i\,i\overset{\leftrightarrow}{\partial}_\mu\,A), \quad H_i = (h, H)$$

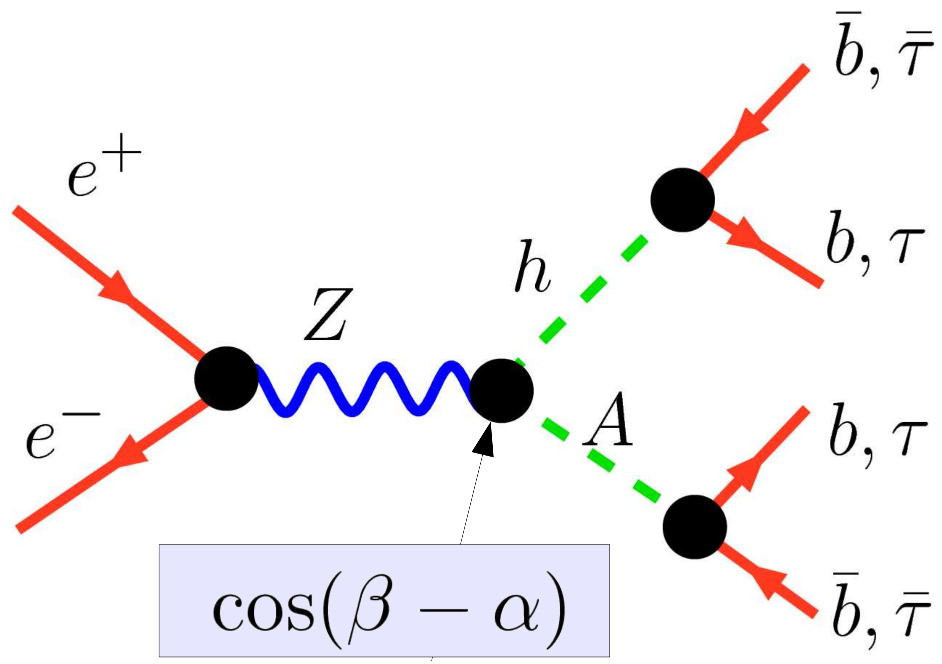
$$\mathcal{L}_{\mathcal{H}H^\pm W^\mp} = -\frac{g}{2}\,g_{\mathcal{H}H^+W^-}\,W^{-\mu}(\mathcal{H}\,i\overset{\leftrightarrow}{\partial}_\mu\,H^+) + \text{h.c.}, \quad \mathcal{H} = (h, H, A)$$

Sum rule:
blue^2+red^2=1



No lose?





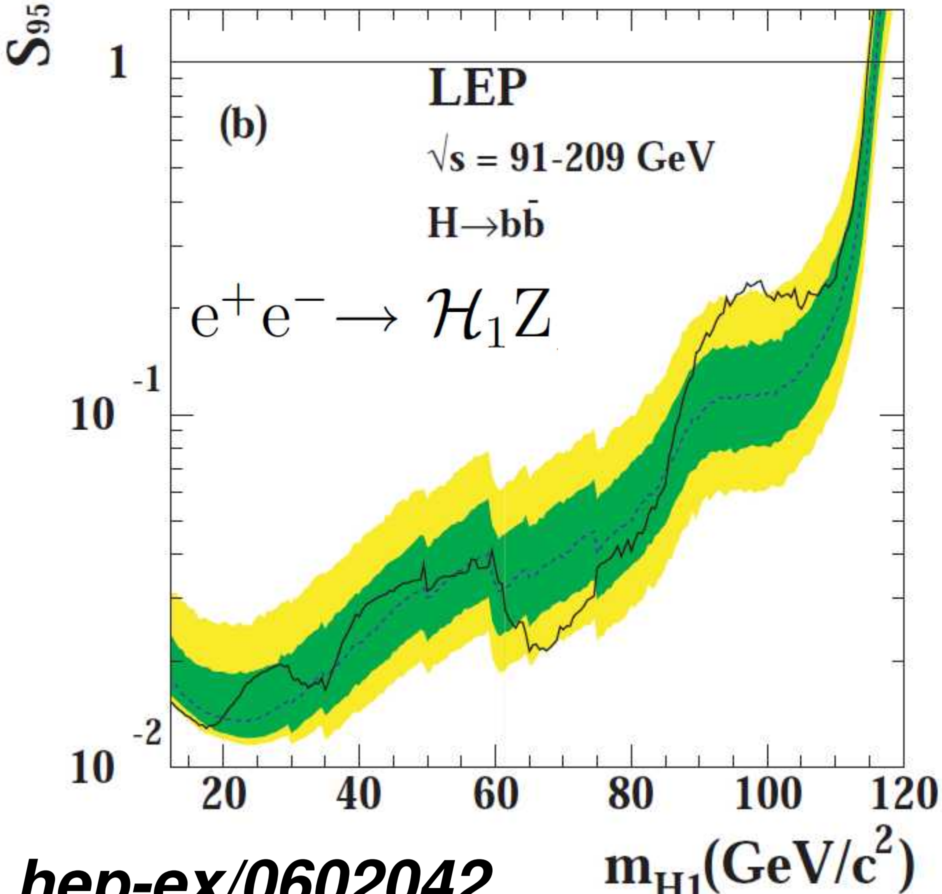
$$g^2_{ZZh} + g^2_{ZAh} = 1$$

- ***Zh and Ah channels are highly complementary!***

Both channels has been studies at LEP2

$S_{95} = g^2_{ZZh} \times Br(h \to b\bar{b})$

$S_{95} = g^2_{ZAh} \times Br(h \to b\bar{b}) \times Br(A \to b\bar{b})$



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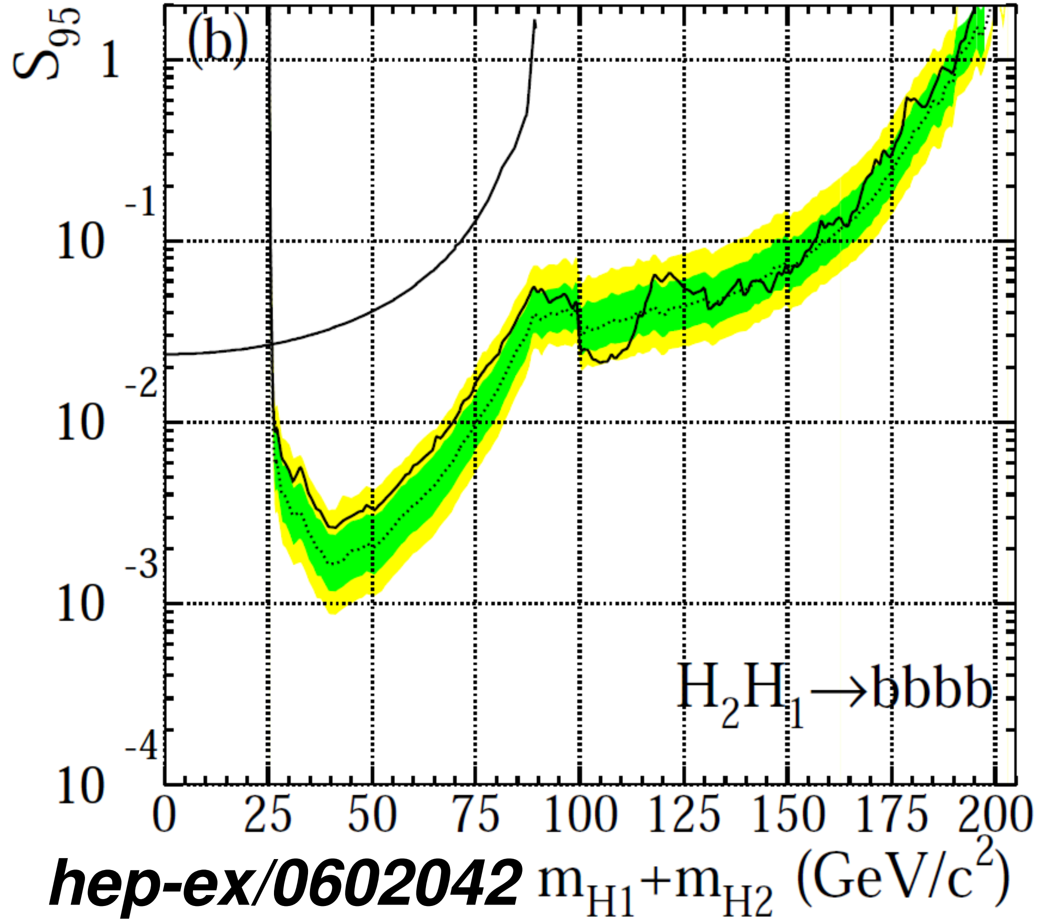

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Similar limits are for H->ττ channel,

but Br(H->ττ) is one order of magnitude smaller then Br(H->bb)

Higgs mixing and radiative corrections

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha \\ c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} Reh_d^0 \\ Reh_u^0 \end{pmatrix} \qquad -\pi/2 < \alpha < 0$$

at tree-level

$$\begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{21}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} = \begin{pmatrix} M_H^2 & 0 \\ 0 & M_h^2 \end{pmatrix}$$

$$\begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{21}^2 & \mathcal{M}_{22}^2 \end{pmatrix}_{tree} = \begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2 \cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

assuming **tan*β>>1*** ***for simplicity***

- ***decoupling (SM-like light Higgs):***

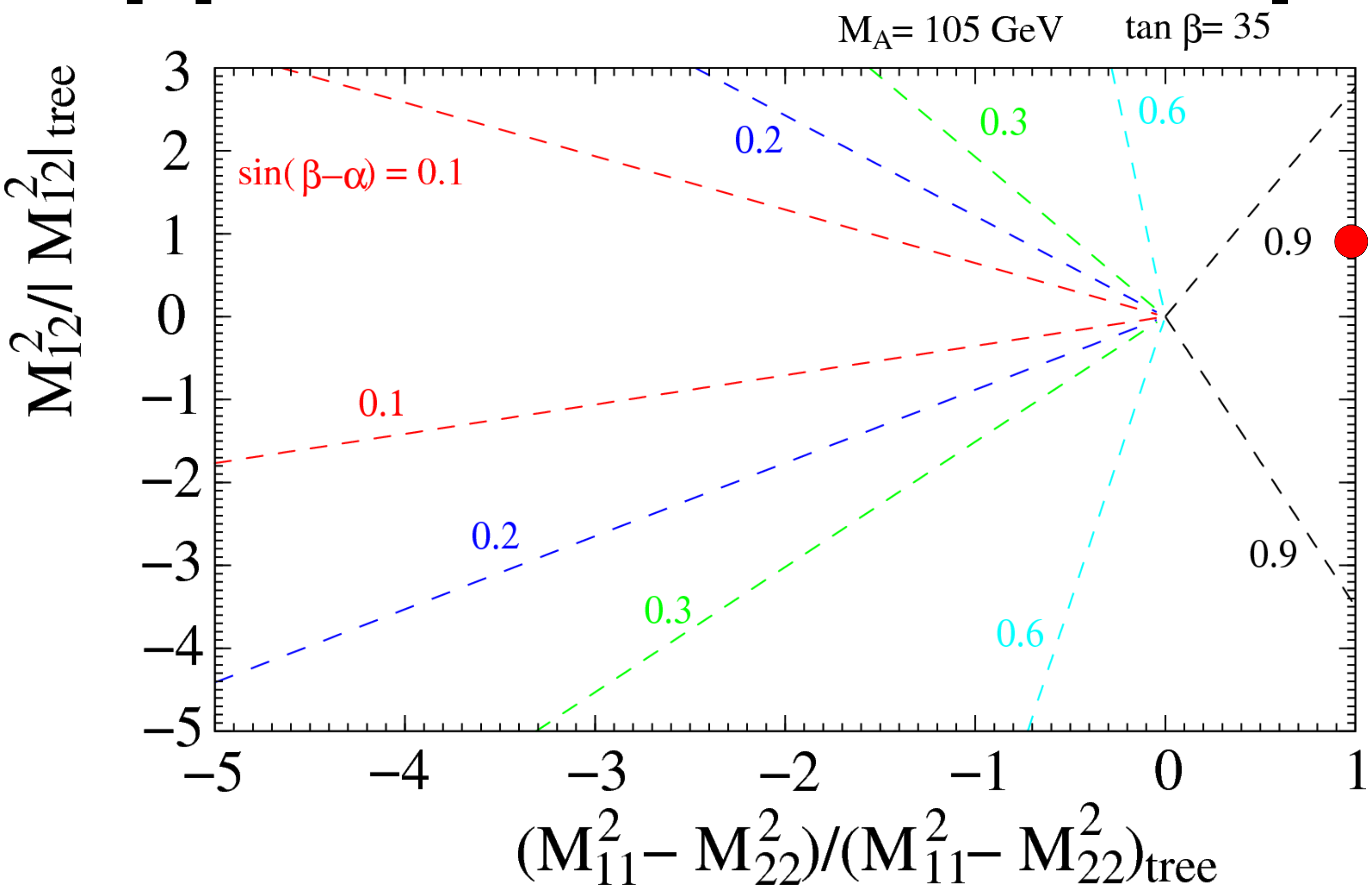
$$M_A >> M_Z : \quad M_{11}^2 >> M_{22}^2, \quad c_\alpha \simeq 1 \Rightarrow \sin(\beta - \alpha) \simeq 1 (\alpha \simeq 0)$$

- ***non-decoupling (non-SM-like light Higgs):***

$$M_A \simeq M_Z : \text{ if } M_{11}^2 < M_{22}^2 \Rightarrow c_\alpha \simeq 0, \sin(\beta - \alpha) \simeq 0 \ (\alpha \simeq -\pi/2)$$

$\mathbf{M_{11}^2 < M_{22}^2}$: never at tree-level but easy realize at 1-loop!

Suppression of ZZh coupling



$M_A \simeq M_Z$: why $M_{11}^2 < M_{22}^2$ is easy?

- ***the lightest neutral Higgs is mainly h_D and*** $\delta\mathcal{M}_{22}^2 \simeq \frac{3y_t^4 v^2 s_\beta^2}{8\pi^2} \ln\left(\frac{M_S^2}{m_t^2}\right)$

$M_h^2 \simeq \mathcal{M}_{11}^2, M_H^2 \simeq \mathcal{M}_{22}^2 \quad \text{and} \quad \mathcal{M}_{11}^2 < \mathcal{M}_{22}^2$

very different from decoupling 'standard' scenario!

Sample point as an example

$\tan\beta$	M_{H^+}	μ	A_t	M_1/M_2	M_3	M_Q
40	130	600	600	100/200	300	300

- **tree level:**

$$\mathcal{M}_0^2 = \begin{bmatrix} (101)^2 & -(22)^2 \\ -(22)^2 & (91)^2 \end{bmatrix}$$

$$\sin(\beta-\alpha) \simeq 0.98$$

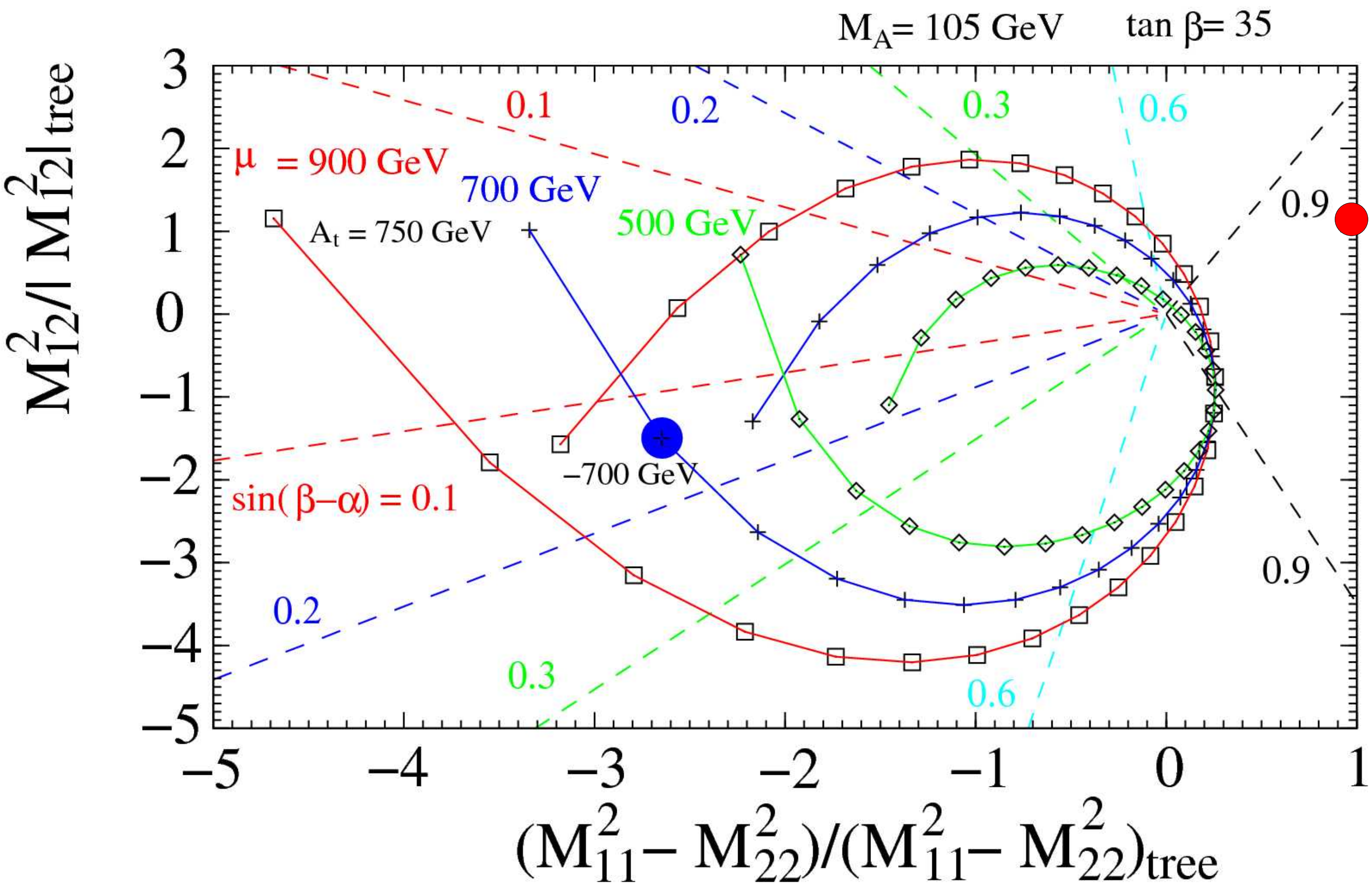
→

- **loop corrected:**

$$\mathcal{M}^2 = \begin{bmatrix} (86)^2 & -(38)^2 \\ -(38)^2 & (119)^2 \end{bmatrix}$$

$$\sin(\beta-\alpha) \simeq 0.22$$

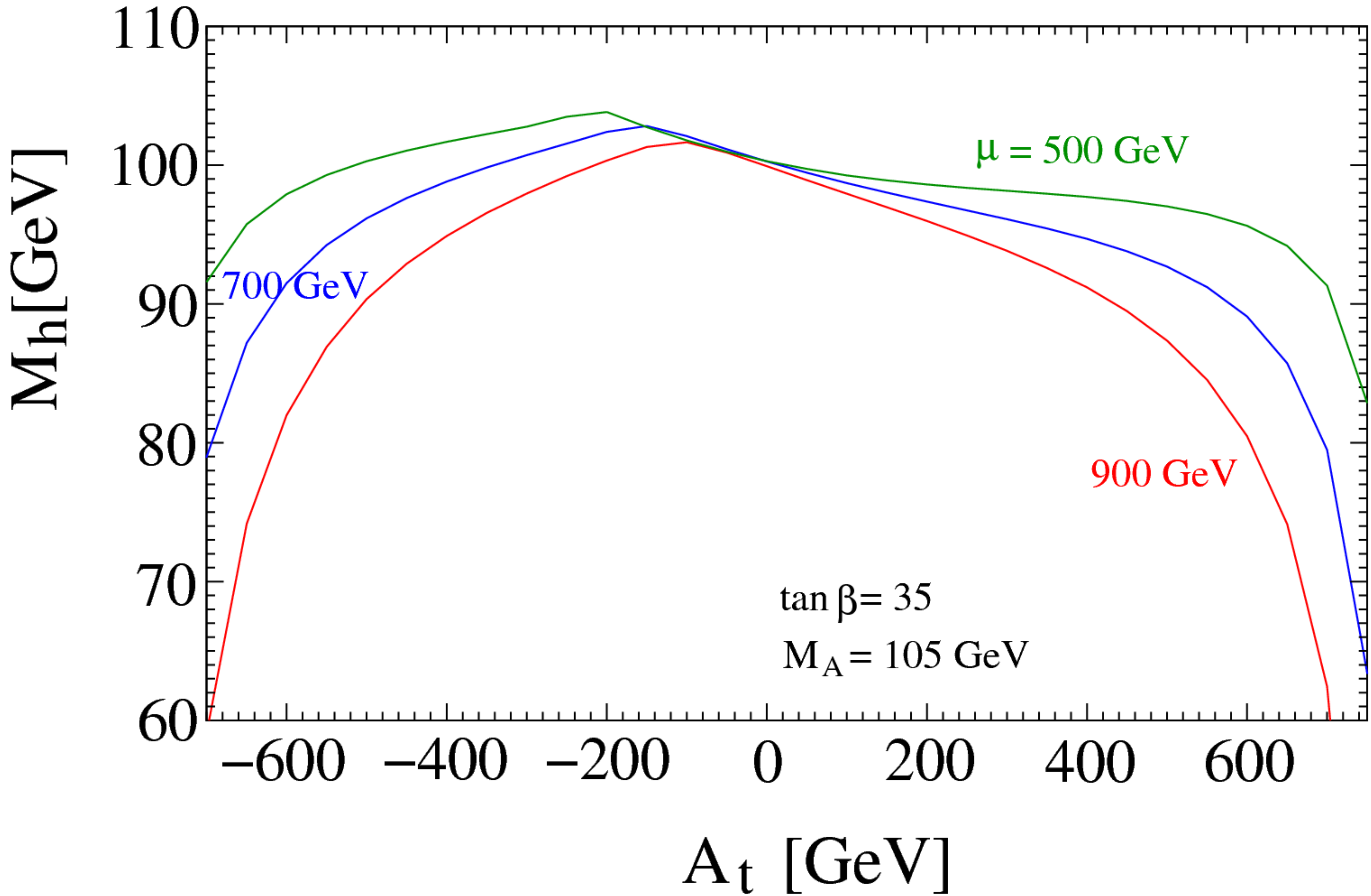
Suppression of ZZh coupling



- ***additional 'help' from*** $|A_t|, \mu > 400 \text{ GeV}$ ***is important!***

$$\delta\mathcal{M}^2_{22} \simeq \frac{3y_t^4 v^2 s_\beta^2}{8\pi^2} \ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{y_t^4 v^2 s_\beta^2}{32\pi^2} \frac{X_t A_t}{M_S^2}\left(12 - \frac{X_t A_t}{M_S^2}\right) - \frac{y_b^4 v^2 s_\beta^2}{32\pi^2}\left(\frac{\mu}{M_S}\right)^4$$

Suppression of the lightest Higgs mass



MSSM parameter scan

Parameter space, CP conserving case

parameter	lower limit	upper limit
$\tan\beta$	1.1	50
M_{H^+}	100	200
μ	-2000	2000
M_1	50	500
M_2	50	500
M_3	50	1000
A_t	-2000	2000
$MQ3$	300	700

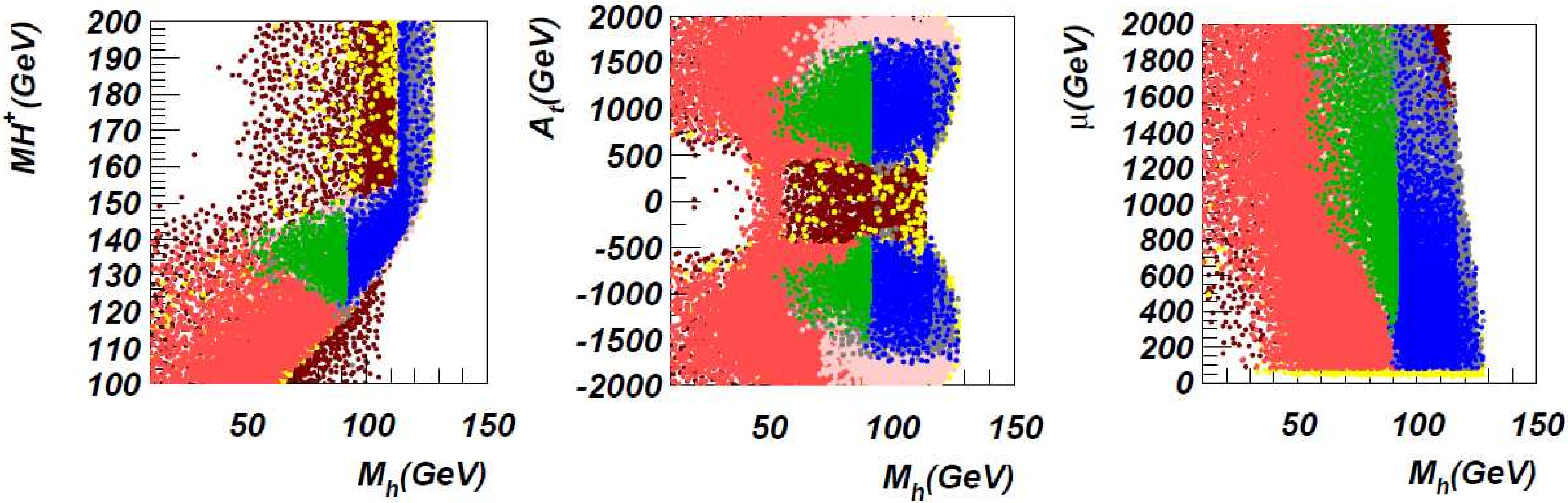
Constraints

LEPII $Z\mathcal{H}$ and $A\mathcal{H}$ constraint $\mathcal{H}=(h,H)$ $g^2_{ZZ\mathcal{H}} \times Br(\mathcal{H}\to b\bar{b}) < F_{Z\mathcal{H}}(M_\mathcal{H})$ $g^2_{ZZh} \times Br(A\to b\bar{b}) \times Br(H\to b\bar{b}) < F_{Ah}$ $g^2_{ZZH} \times Br(A\to b\bar{b}) \times Br(h\to b\bar{b}) < F_{AH}$
$M_{\chi_1^\pm} > 100,\ M_{\tilde{t}_1} > 100,\ M_3 > 270$ GeV
Color breaking constraints $A_t^2 < 3(M^2_{Q3} + M^2_{U3} + \mu^2 + M^2_{H_2})$
$\Delta\rho_{SUSY} < 2\times 10^{-3}$
$b\to s\gamma$ SUSY constraint: $\lvert\Delta Br(b\to s\gamma)\rvert < 1\times 10^{-4}$

CpsuperH is used

(Lee,Pilaftsis,Carena,Choi,Drees,Ellis,Wagner)

Scan Results: ~60 GeV light Higgs boson is allowed!

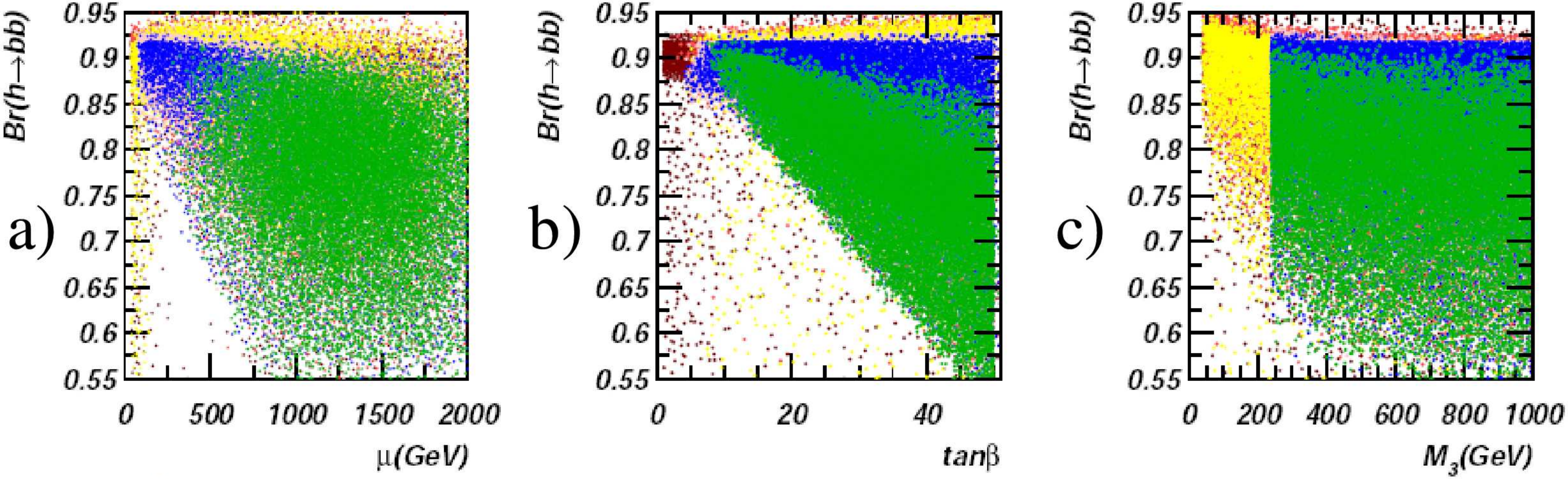


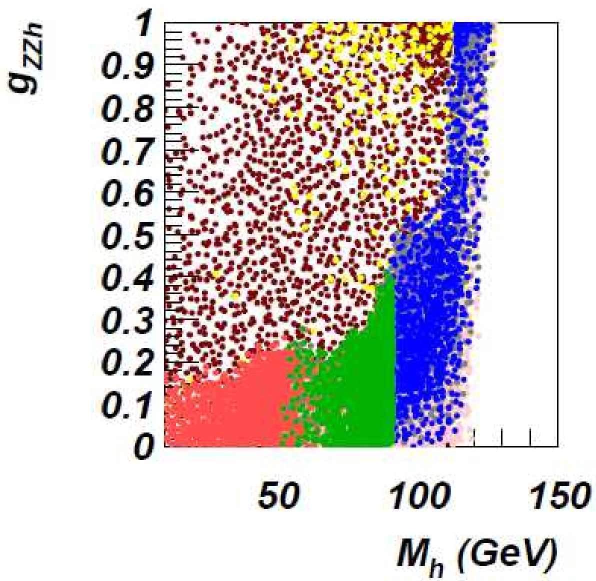
excluded by: ■ *LEP2 Zh search* ■ *LEP2 Ah search* ■ *LEP2/TEV SUSY search*
■ *the color breaking constraint*

allowed: ■ $M_h<M_Z$ ■ $M_h>M_Z$

Key-point: SUSY corrections suppressing ττH and bbH couplings in non-universal way!

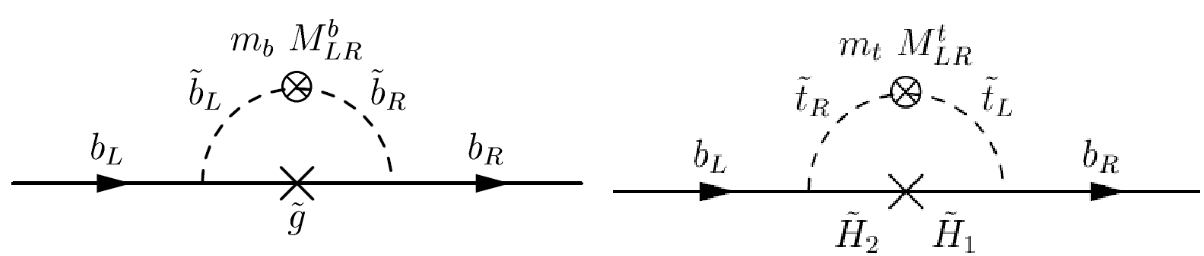
(Carena,Mrenna,Wagner;Borzumati,Farrar,Polonsky; Guasch,Hollik,Penaranda)





$$m_b + \delta m_b = \frac{m_b}{1 + \Delta m_b}$$

$$(\Delta m_b)_{\mathrm{SUSY-QCD}} \propto + \frac{2\alpha_S(M_\mathrm{S})}{3\pi}\, m_{\tilde{g}}\, \mu \tan\beta$$



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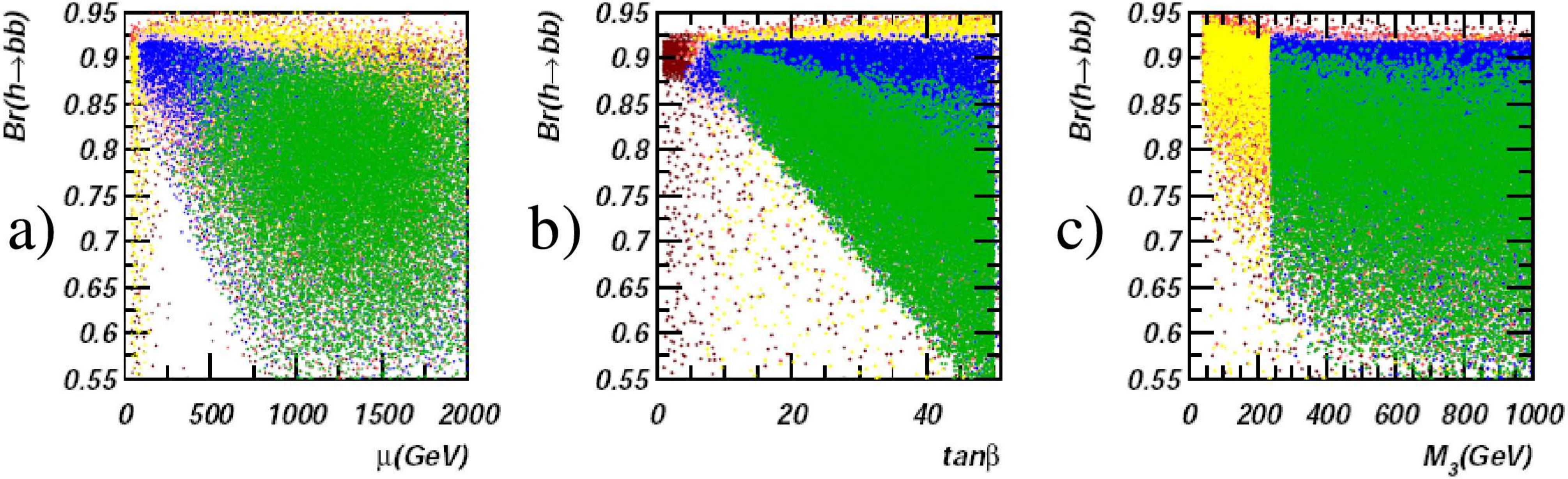

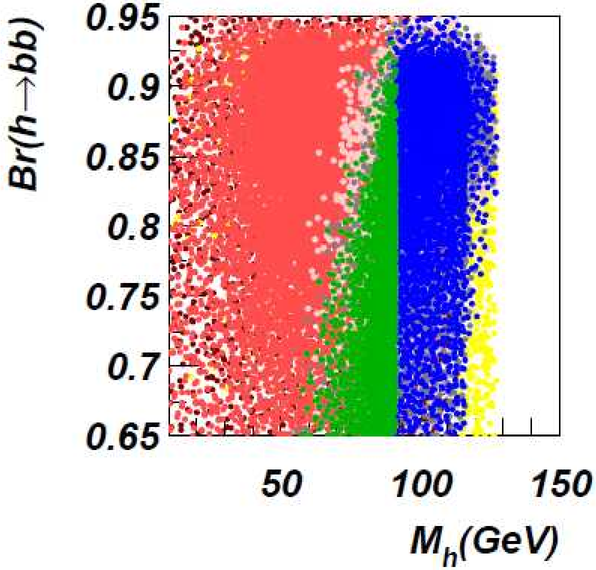

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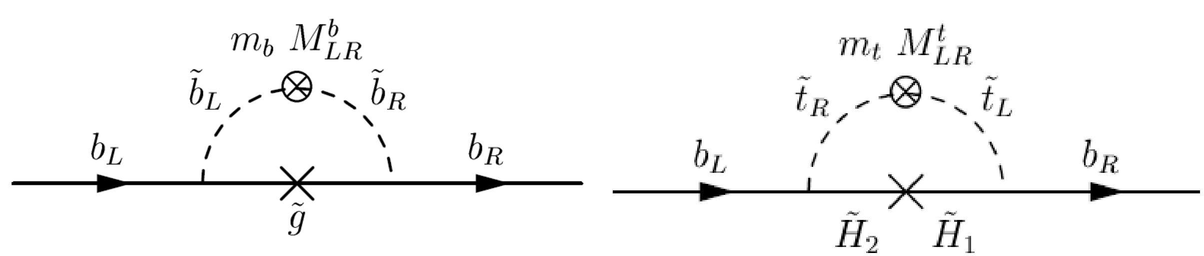
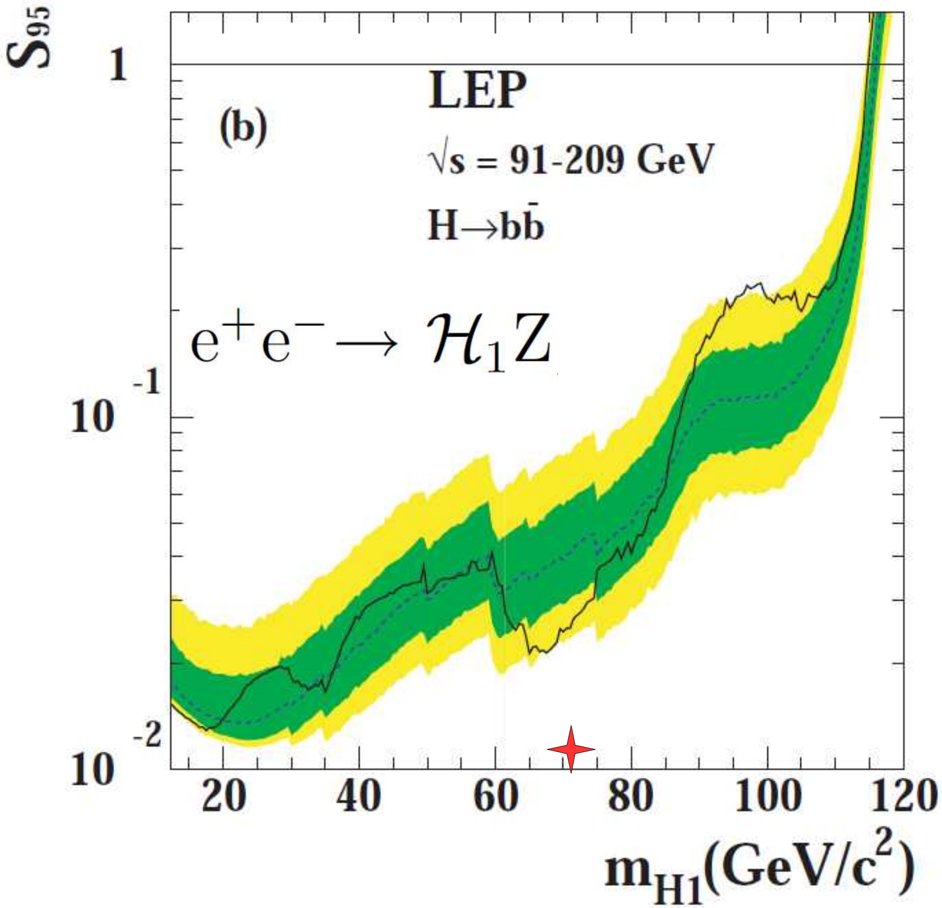
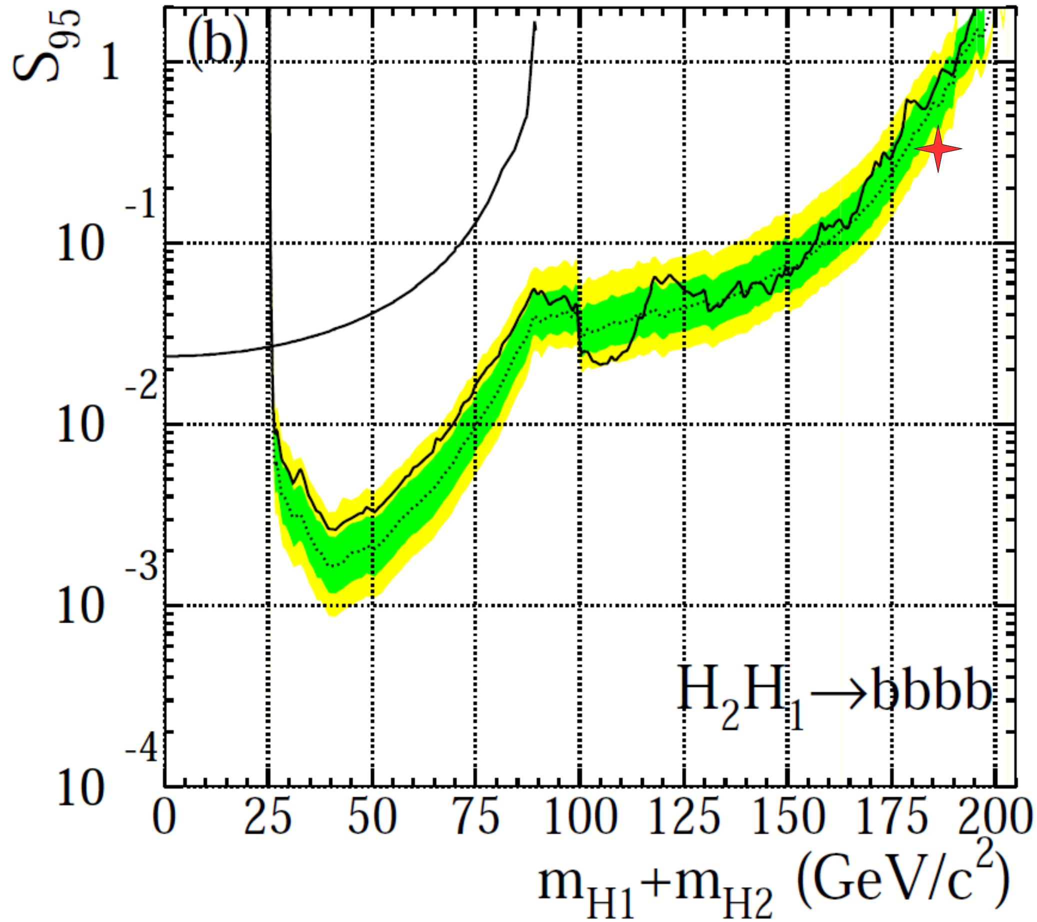


LHS sample point

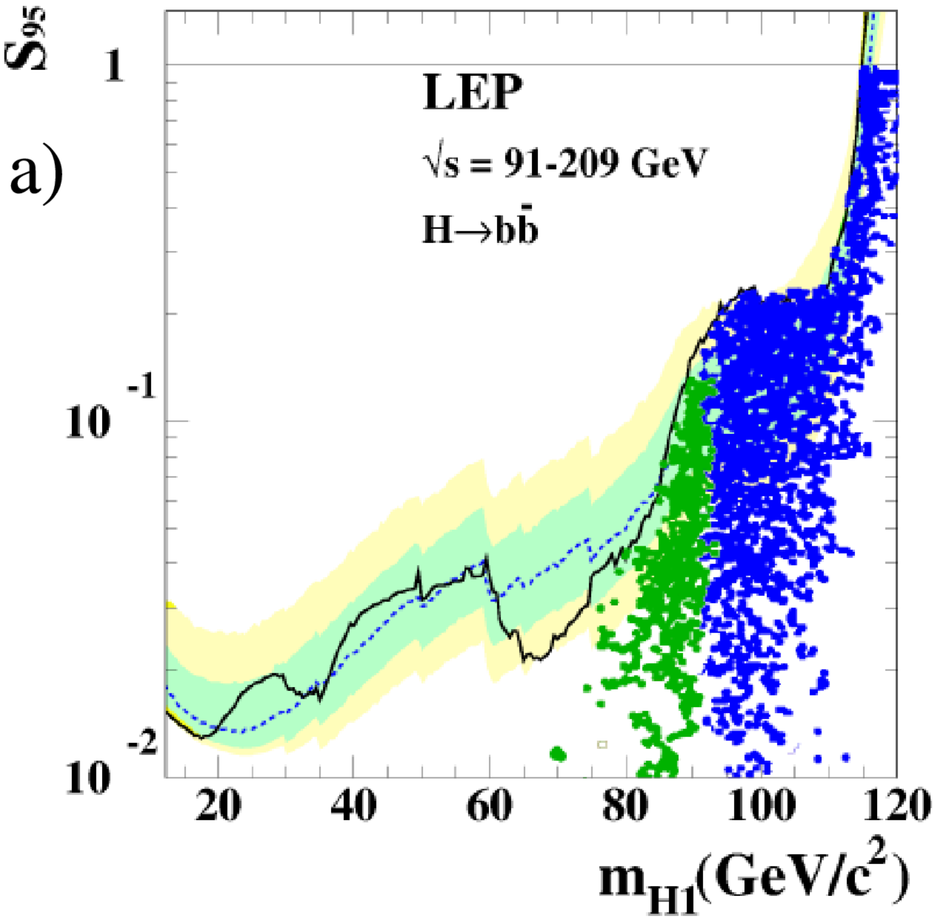


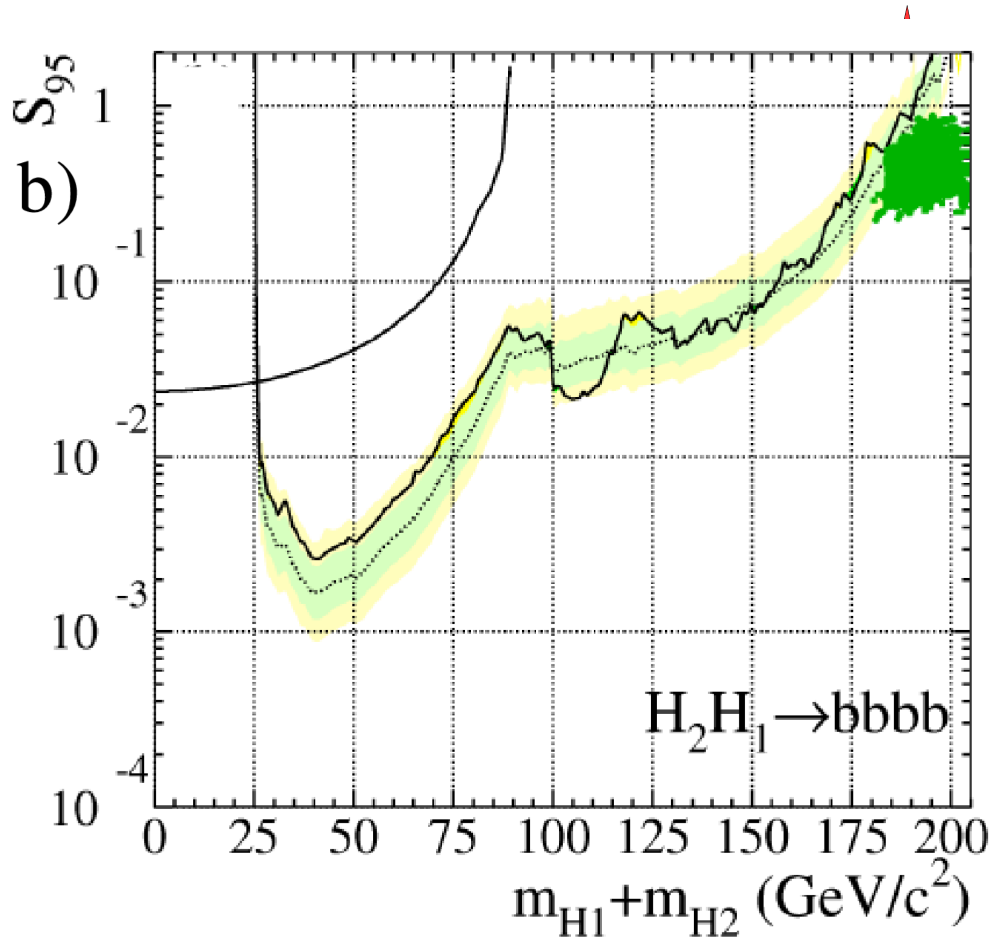


$\tan\beta$	M_{H+}	μ	A_3	M_1	M_2	M_3	M_Q
35	135	890	750	100	200	600	330

$$\boldsymbol{M_h = 71,\ M_A = 113,\ M_H = 119}$$
$$\mathrm{Br}(h/A/H \to b\bar{b}) = 0.65/0.64/0.03$$
$$\mathrm{Br}(h/A/H \to \tau\bar{\tau}) = 0.25/0.34/0.54$$
$$g^2_{ZZh} = 0.006,\ g^2_{ZZH} = g^2_{H^+W^-h} = 0.994$$
$$M_{\tilde{\chi}^0_1} = 100,\ M_{\tilde{\chi}^+_1} = 198,\ M_{\tilde{t}_1} = 126,\ M_{\tilde{b}_1} = 273$$
$$\Delta\rho = 6.7 \times 10^{-4}$$

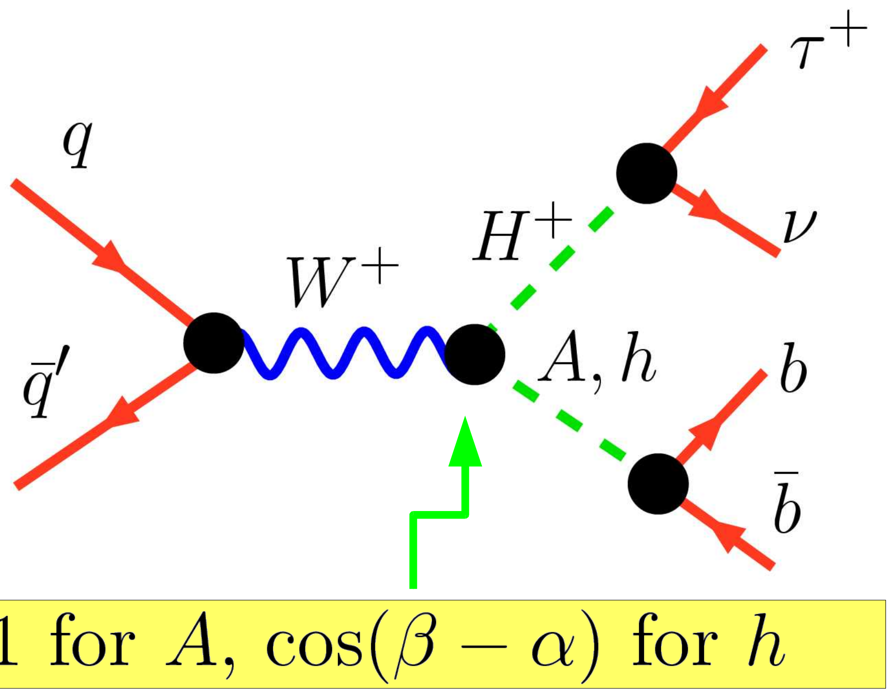
LHS parameter space versus LEP2 constraints





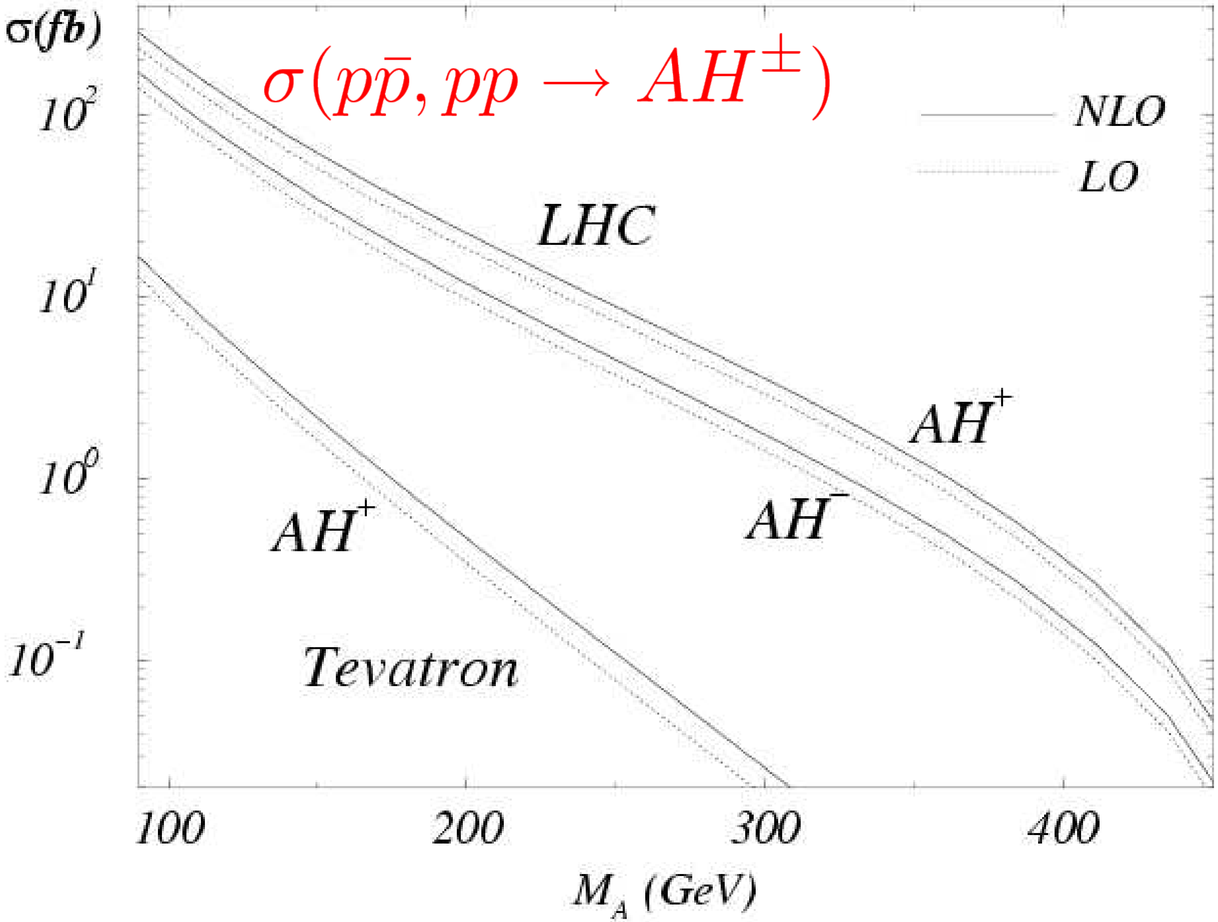
Associated production of Charged – Neutral Higgses would a perfect test of LHS

- *large $WH^{+}h$ coupling scenario makes $H^{+}h$ ($H^{+}A$) associate production very special: complementary to LEPII*



- $g_{AH^{+}W^{-}} = 1$ *: does not depend on SUSY parameters at tree-level*

$H^{+}A$ signal rate

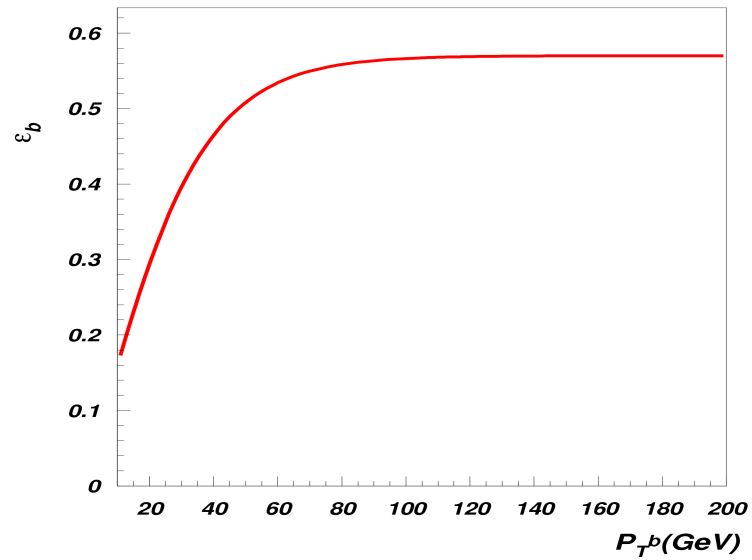


Q.-H. Cao, S. Kanemura, C.-P. Yuan
hep-ph/0311083

NLO QCD correction is about 20%

Signal / background study

- $q\bar{q} \to W^* \to A(\to b\bar{b})H^+(\to \tau^+\nu)$ **process**
  - $b\bar{b}\pi^+ \; \not{E}_T$ ***signature***



- **backgrounds, cuts**

$$q\bar{q}' \to W^+ b\bar{b}, \quad q\bar{q}' \to t\bar{b},$$
$$q\bar{q} \to t\bar{t}, \quad qg \to q' t\bar{b}$$

- ***P_T-dependent b-tagging:*** $\varepsilon_b = 0.57 \times \tanh\left(\frac{p_T^b}{35\,\mathrm{GeV}}\right)$
- ***basic cuts:***

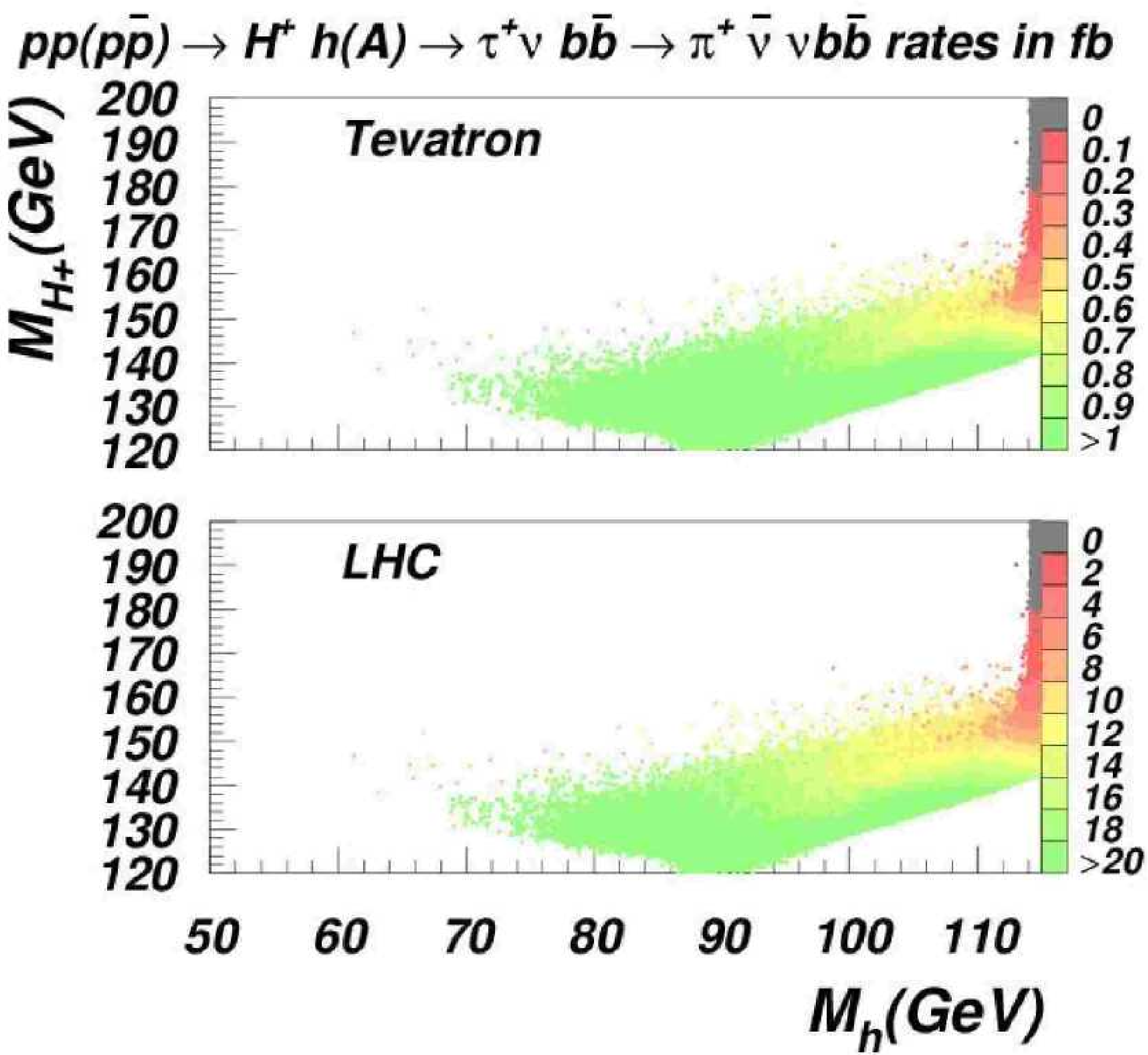
$$P_T(b,\bar{b},\pi^+) > 15\,\mathrm{GeV}, \quad |\eta(b,\bar{b},\pi^+)| < 3.5, \quad \Delta R(b,\bar{b},\pi^+) > 0.4$$
$$p_T(\mathrm{lepton}) > 10\,\mathrm{GeV}, \mathrm{and}\ |\eta(\mathrm{lepton})| < 2.5$$

+ veto for jets and leptons in the central region:

$$p_T(\mathrm{jet}) > 10\,\mathrm{GeV}, \mathrm{and}\ |\eta(\mathrm{jet})| < 3.5$$

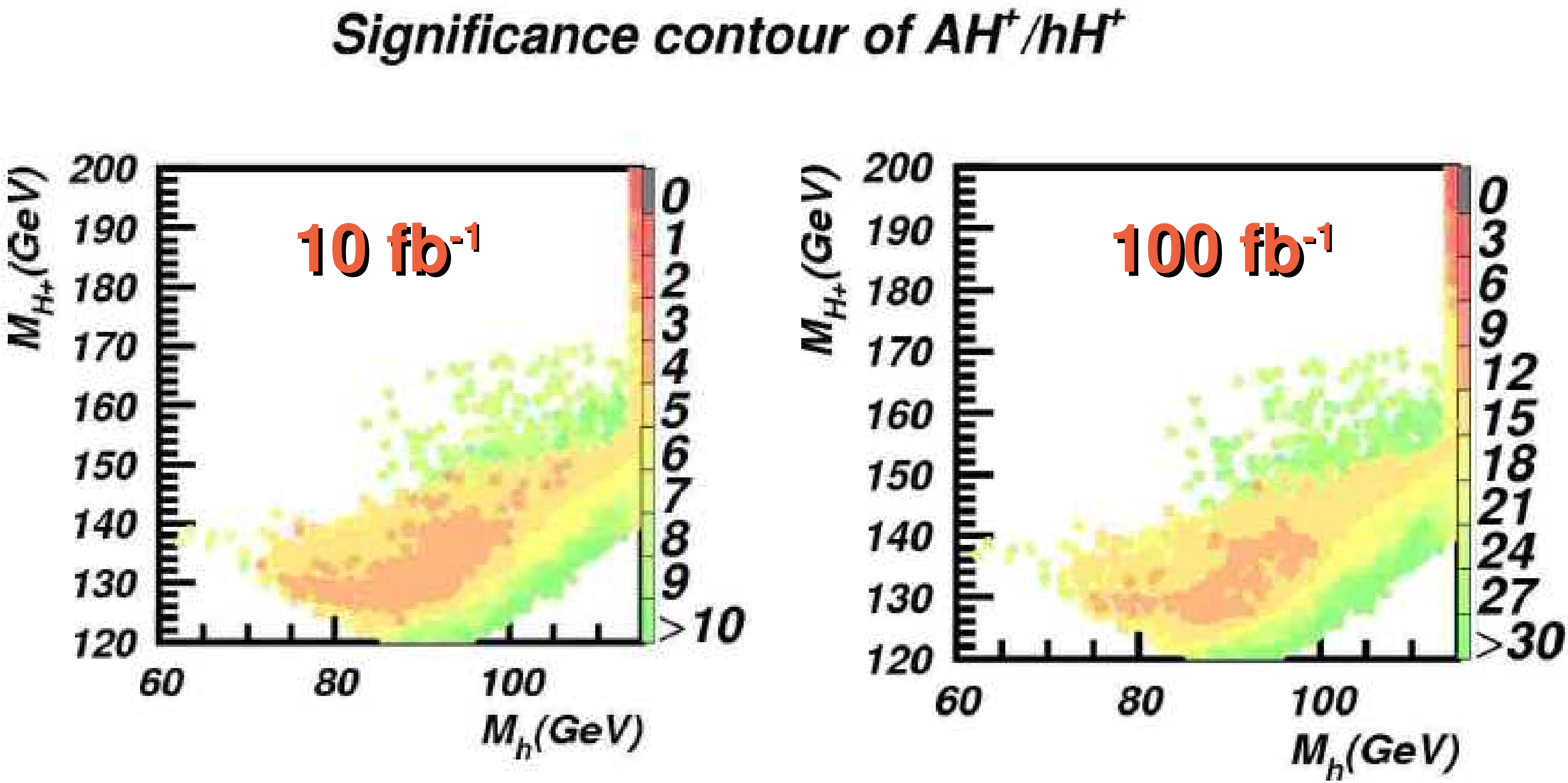
- ***hard cuts:*** $\not{E}_T > 50\,\mathrm{GeV}, \; p_T^\pi > 40\,\mathrm{GeV}, \; |m_{b\bar{b}} - m_A| < 10\,\mathrm{GeV}$

Tevatron/LHC H^+A production rates



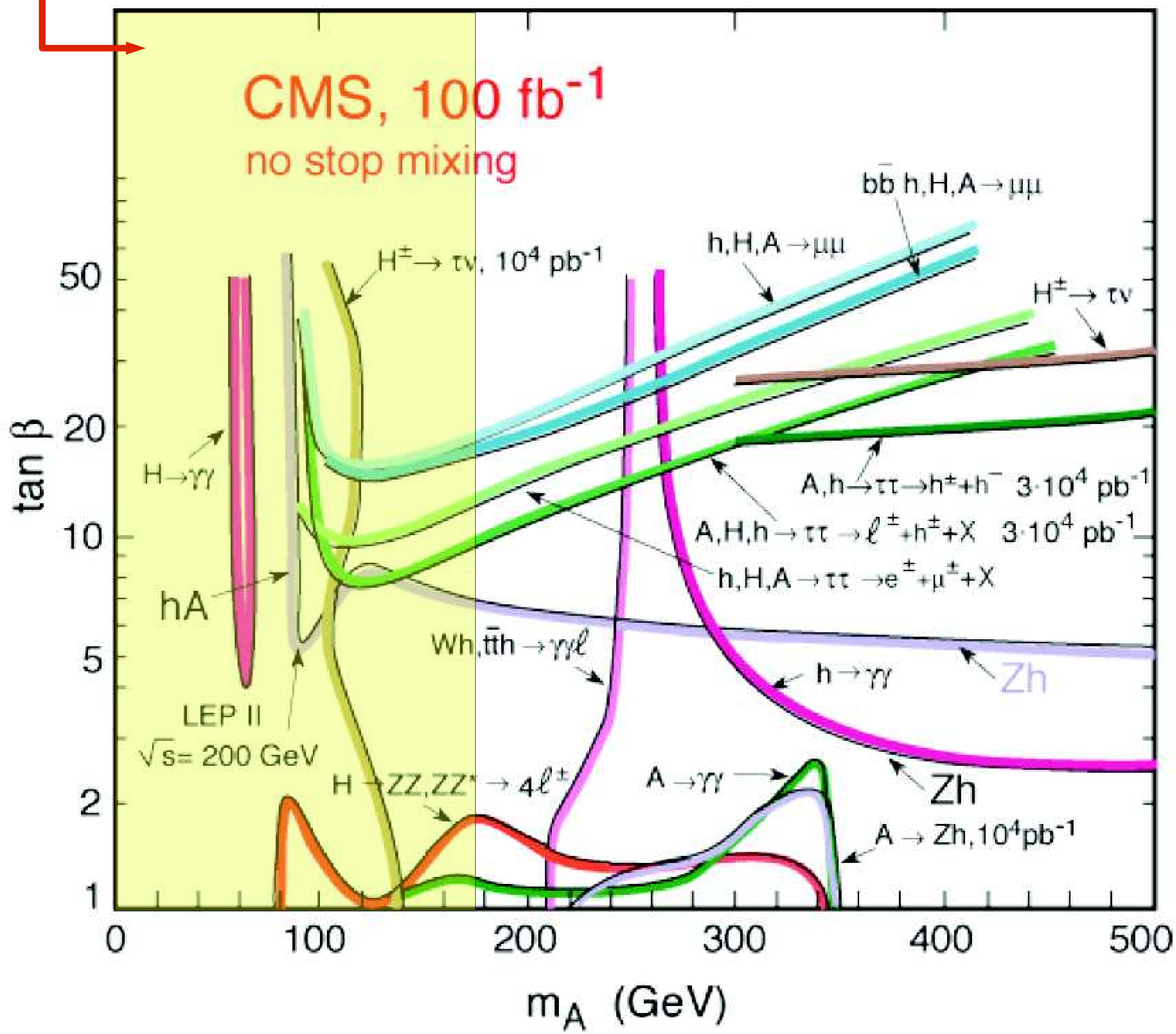
LHC is sensitive to ~1fb level rate for this signature with 100 fb^{-1} integrated luminosity

10 fb^{-1} and 100 fb^{-1} LHC reach for $H^{+}A$ production



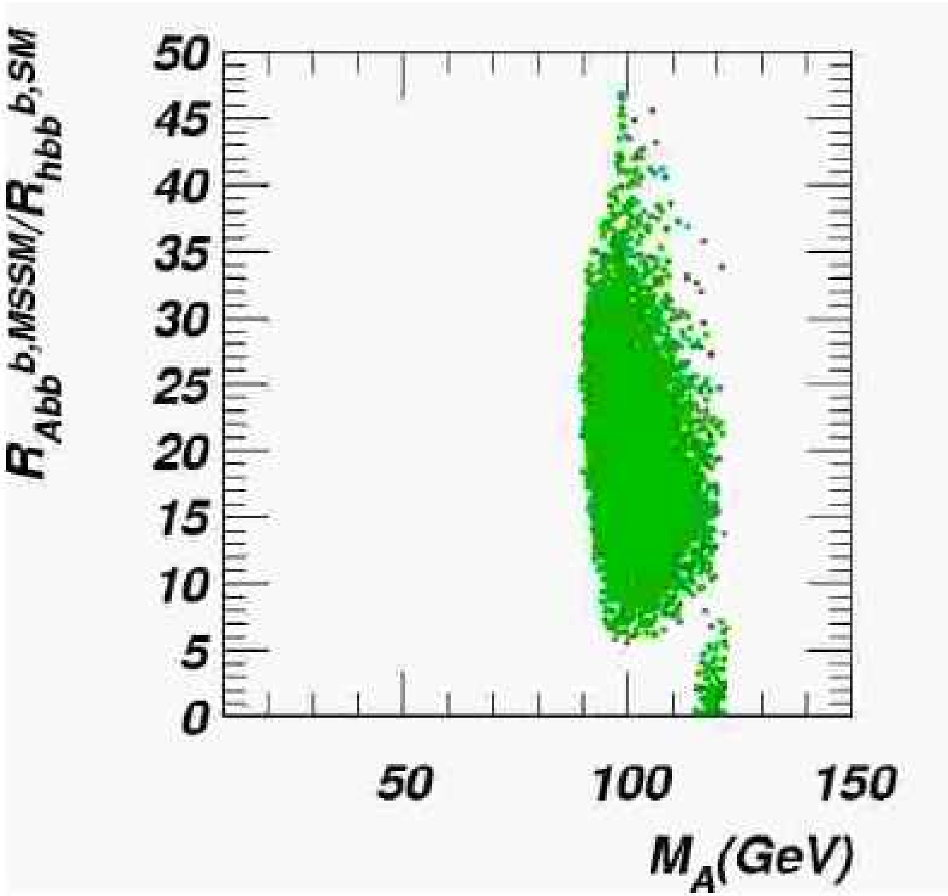
Projecting on to tanβ – M_A plane

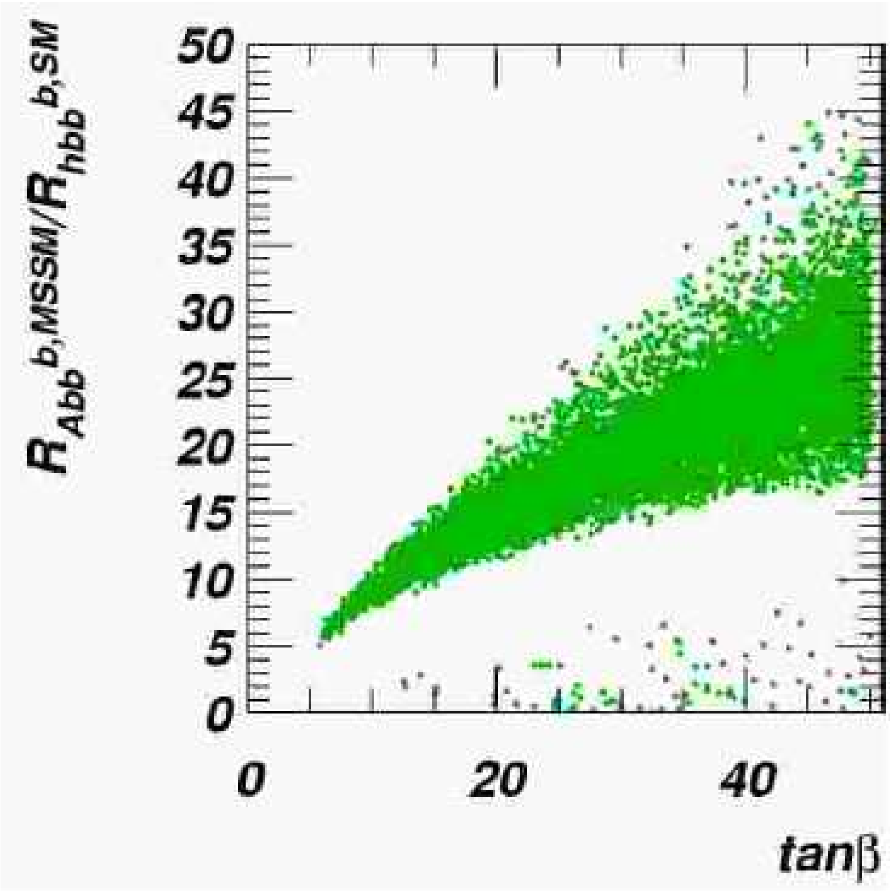
H^+A



Further LHC prospects for Yukawa enhanced processes

$$Y_{MSSM}/Y_{SM} \times \sqrt{Br_{MSSM}/Br_{SM}} \leftrightarrow \tan\beta$$





not using tanβ axes !

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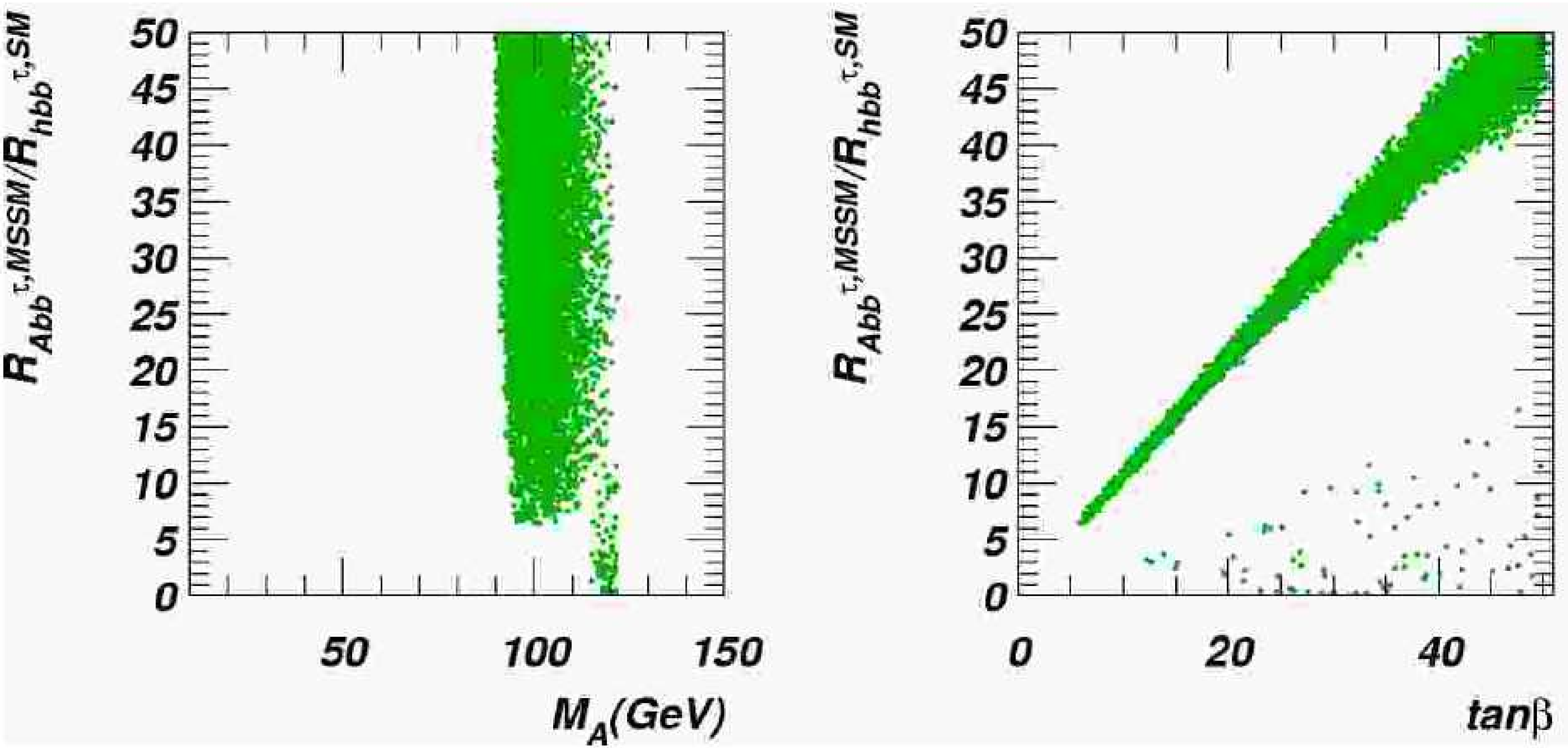


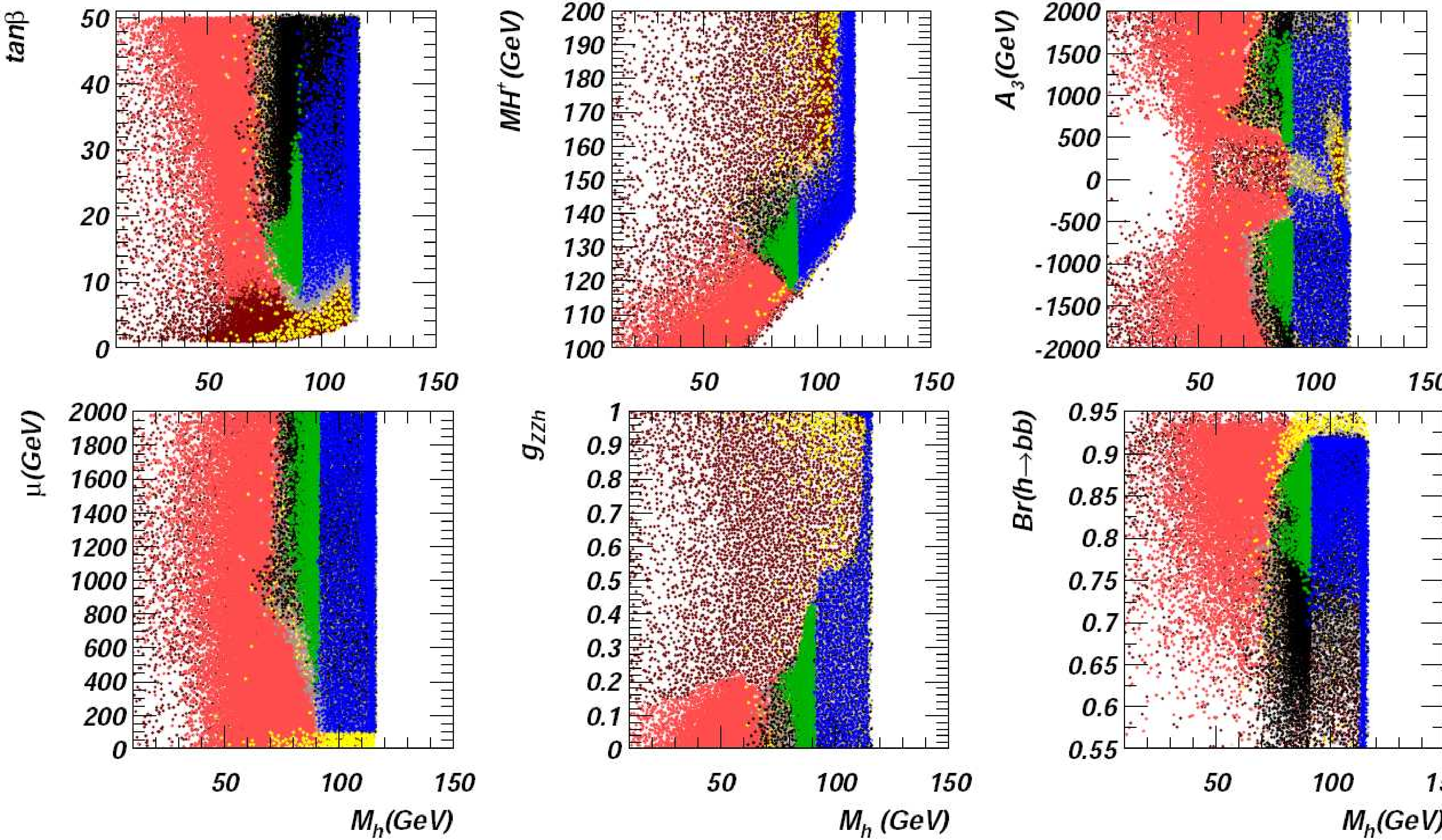
not using tanβ axes !

LHS: features/consequences

- **Light MSSM Higgs ~ 60 GeV mass is allowed!**
  - ***Light Charged Higgs***
    - small ZZh coupling and large WH^+h coupling
  - ***Intermediate – large μ and A_t***
    - Large $\mu>0$ and intermediate-heavy gluino provide non-universal corrections to tau and bottom Yukawa couplings suppressing Br(H->bb)
  - ***Intermediate-high tanβ***
    - provides futher suppression of Br(H->bb), in agreement with b->sγ. Light stops and charginos!
- **H^+A : LHC covers the whole LHS parameter space, suggested process is independent of tanβ**
- **Correlation with Yukawa-enhanced processes, ILC precision tests**
- **Important tests from B-physics experimets!**
- **Different look at fine-tuning problem (especially for ~90 GeV M_H)**

Backup slides

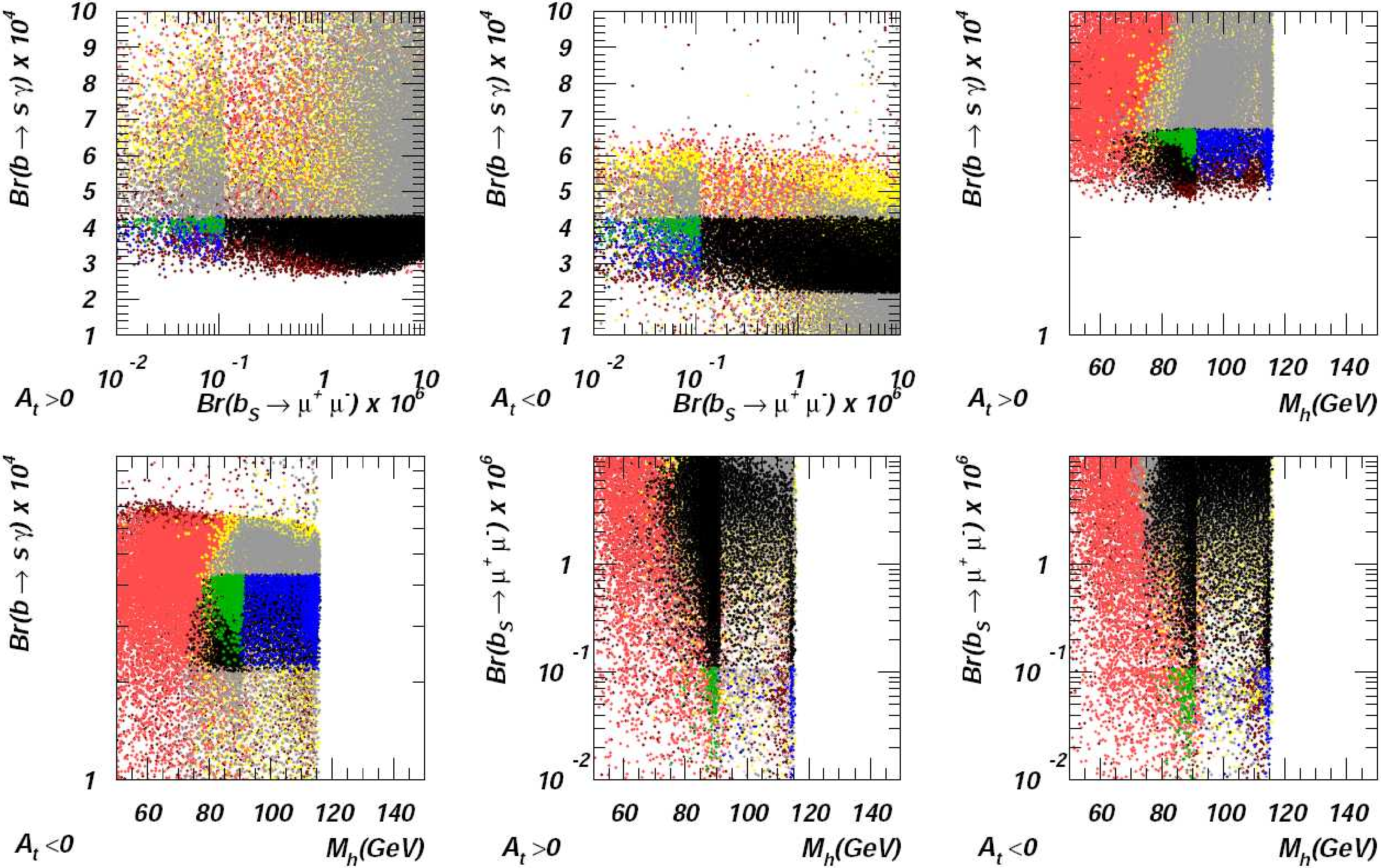
B-physics constraints: μ>0 case



excluded by: LEP2 Zh search, LEP2 Ah search, LEP2/TEV SUSY search, the color breaking constraint, $Br(b \to s\gamma)$ constraint, $Br(B_s \to \mu\mu)$ constraint

allowed: $M_h<M_Z$, $M_h>M_Z$

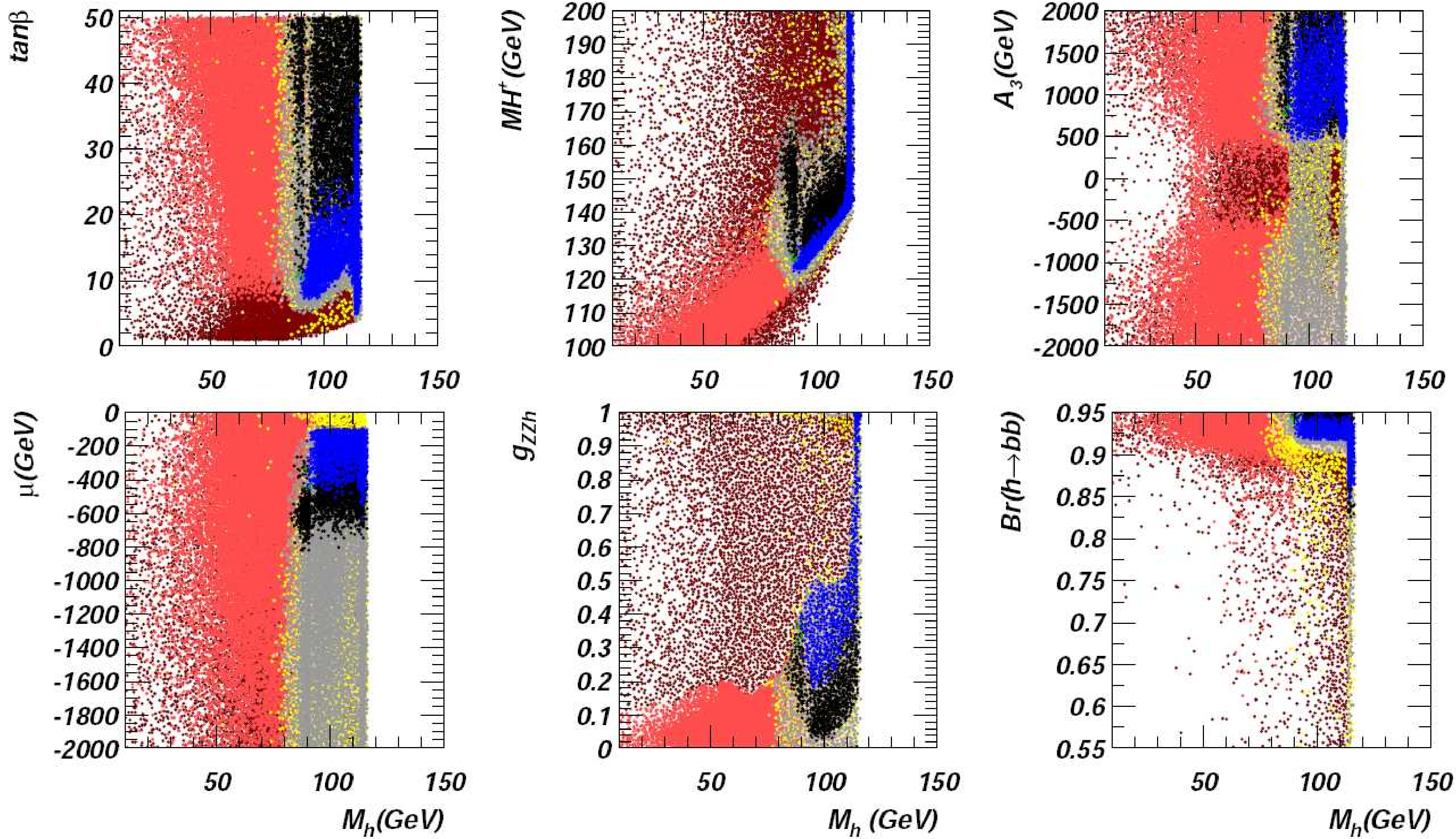
B-physics constraints: μ>0 case



excluded by: LEP2 Zh search; LEP2 Ah search; LEP2/TEV SUSY search; the color breaking constraint; $Br(b \to s\gamma)$ constraint; $Br(B_s \to \mu\mu)$ constraint

allowed: $M_h < M_Z$; $M_h > M_Z$

B-physics constraints: $\mu<0$ case

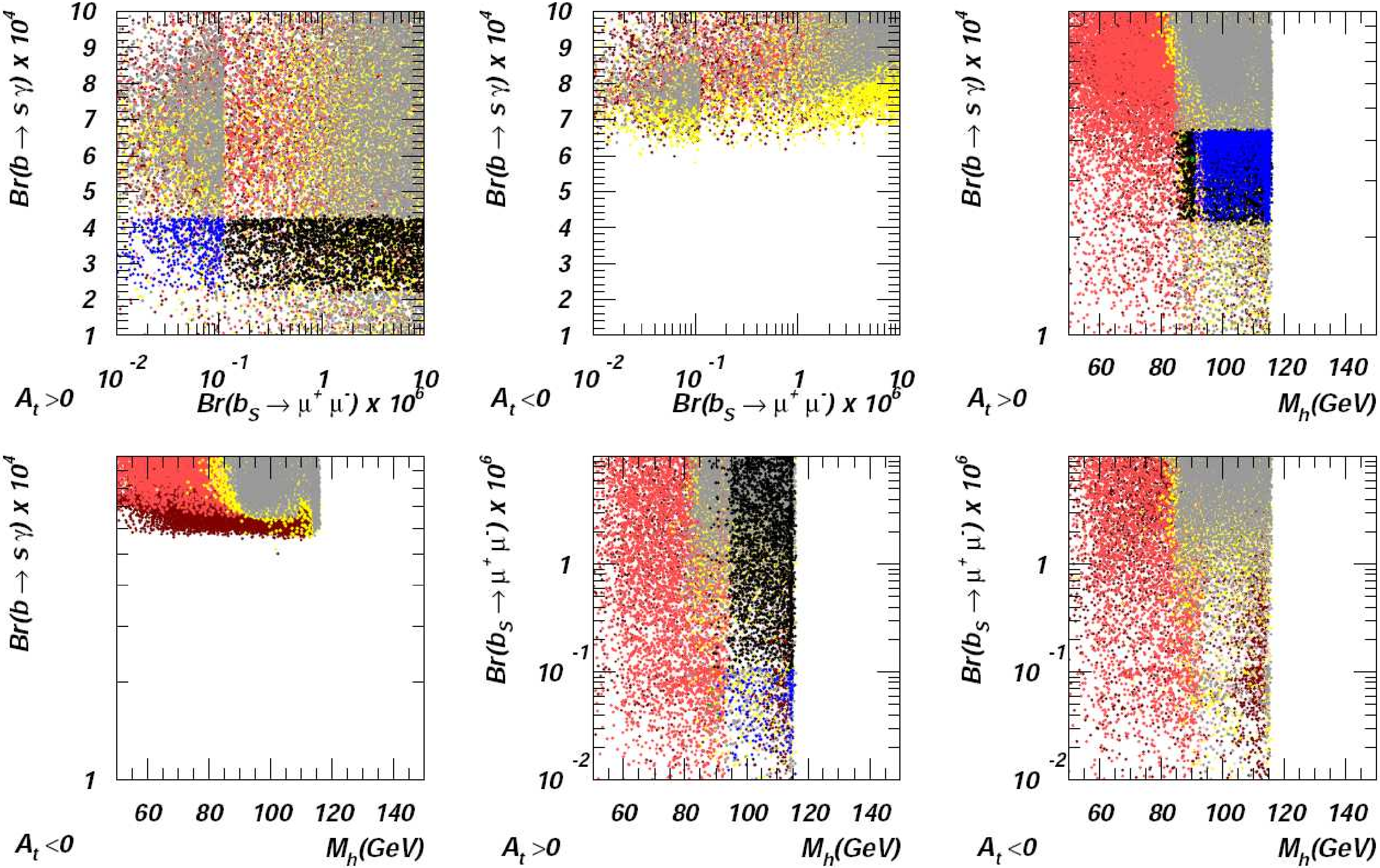


excluded by: ■ LEP2 Zh search ■ LEP2 Ah search ■ LEP2/TEV SUSY search

■ the color breaking constraint ■ $Br(b \to s\gamma)$ constraint ■ $Br(B_s \to \mu\mu)$ constraint

allowed: ■ $M_h<M_Z$ ■ $M_h>M_Z$

B-physics constraints: μ<0 case



excluded by: ■ LEP2 Zh search ■ LEP2 Ah search ■ LEP2/TEV SUSY search

■ the color breaking constraint ■ $Br(b \to s\gamma)$ constraint ■ $Br(B_s \to \mu\mu)$ constraint

allowed: ■ $M_h < M_Z$ ■ $M_h > M_Z$

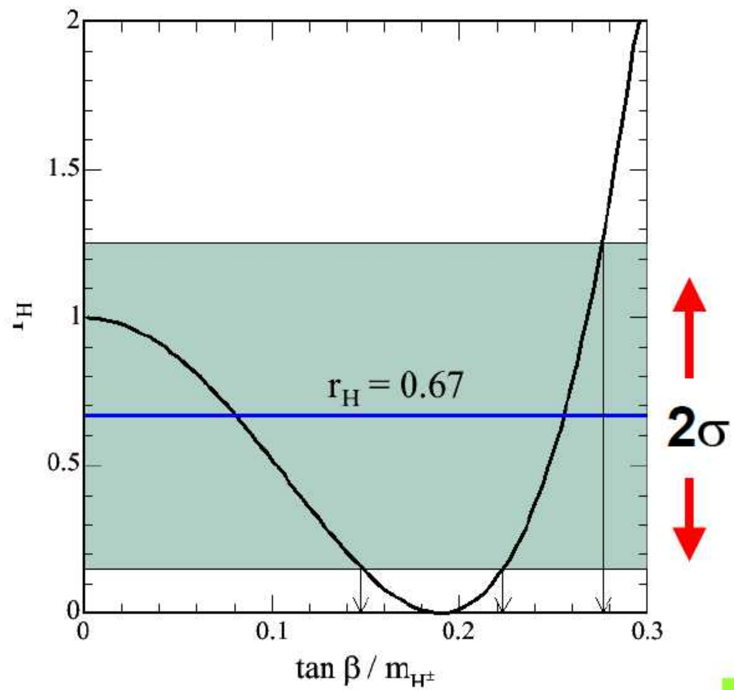
New BELLE results: charged Higgs constraints consistent with Lh scenario!

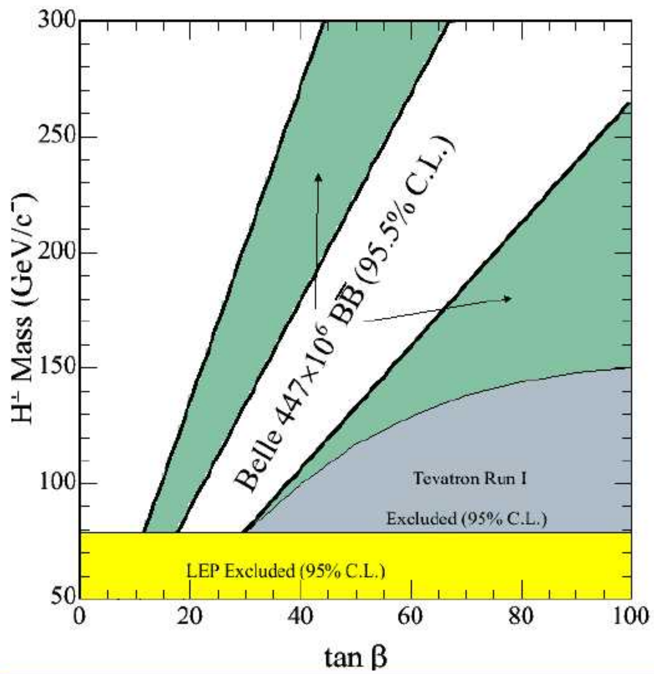
$$\mathcal{B}(B\to\tau\nu) = \mathcal{B}(B\to\tau\nu)_{\mathrm{SM}} \times r_H$$

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2 \rightarrow r_H = 0.67^{+0.29}_{-0.26}$$

$$\mathcal{B}(B\to\tau\nu) = (1.06^{+0.34}_{-0.28}(\mathrm{stat})^{+0.18}_{-0.16}(\mathrm{syst}))\times 10^{-4}$$

$$\mathrm{SM}: \mathcal{B}(B\to\tau\nu) = (1.59 \pm 0.40)\times 10^{-4}$$

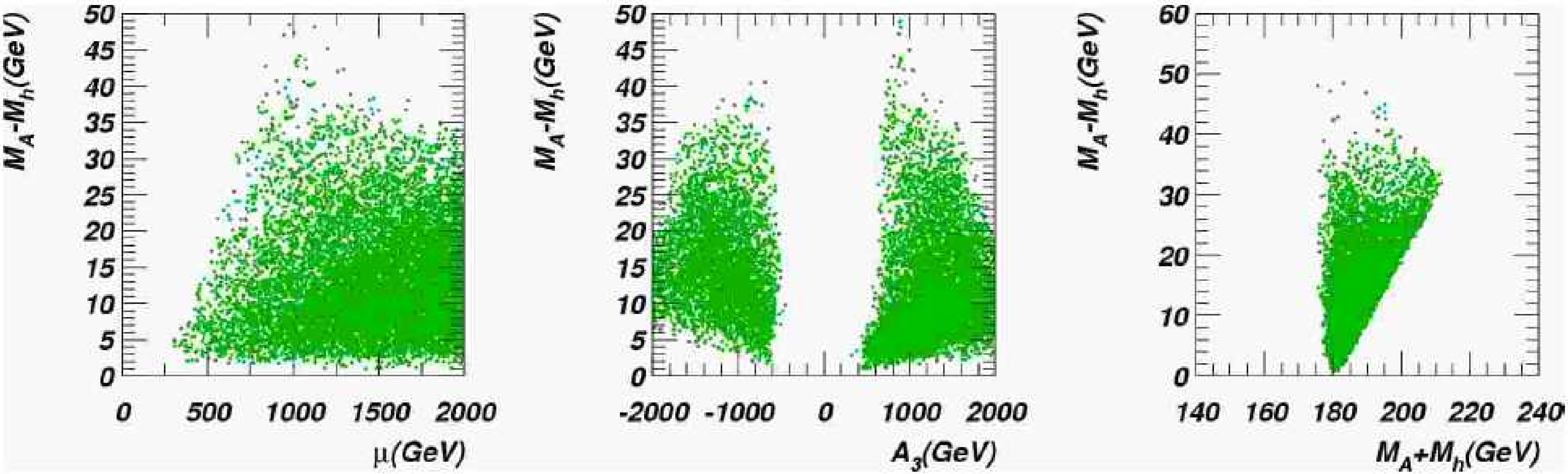




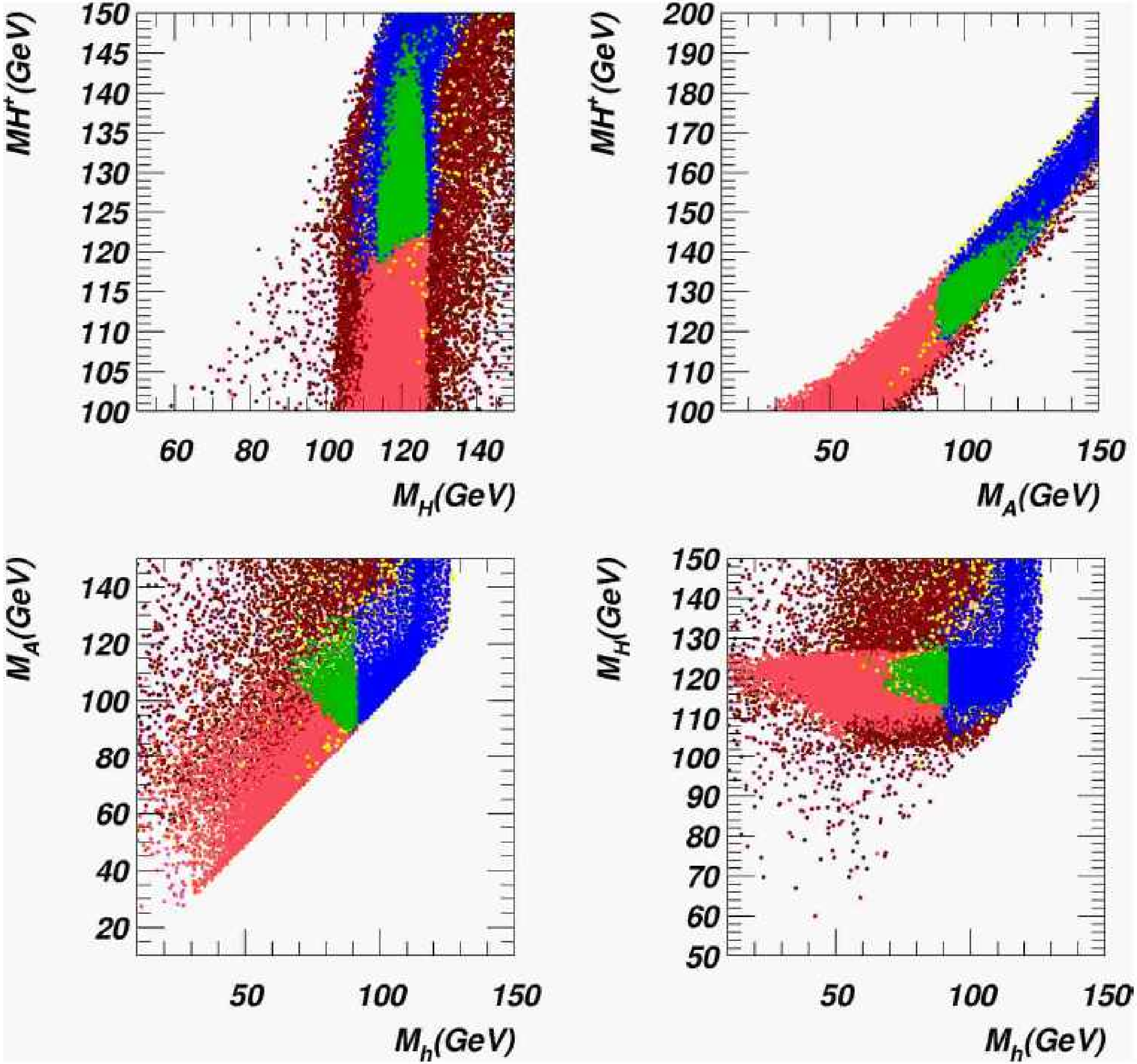
95.5%C.L. exclusion boundaries

Koji Ikado FPCP 2006

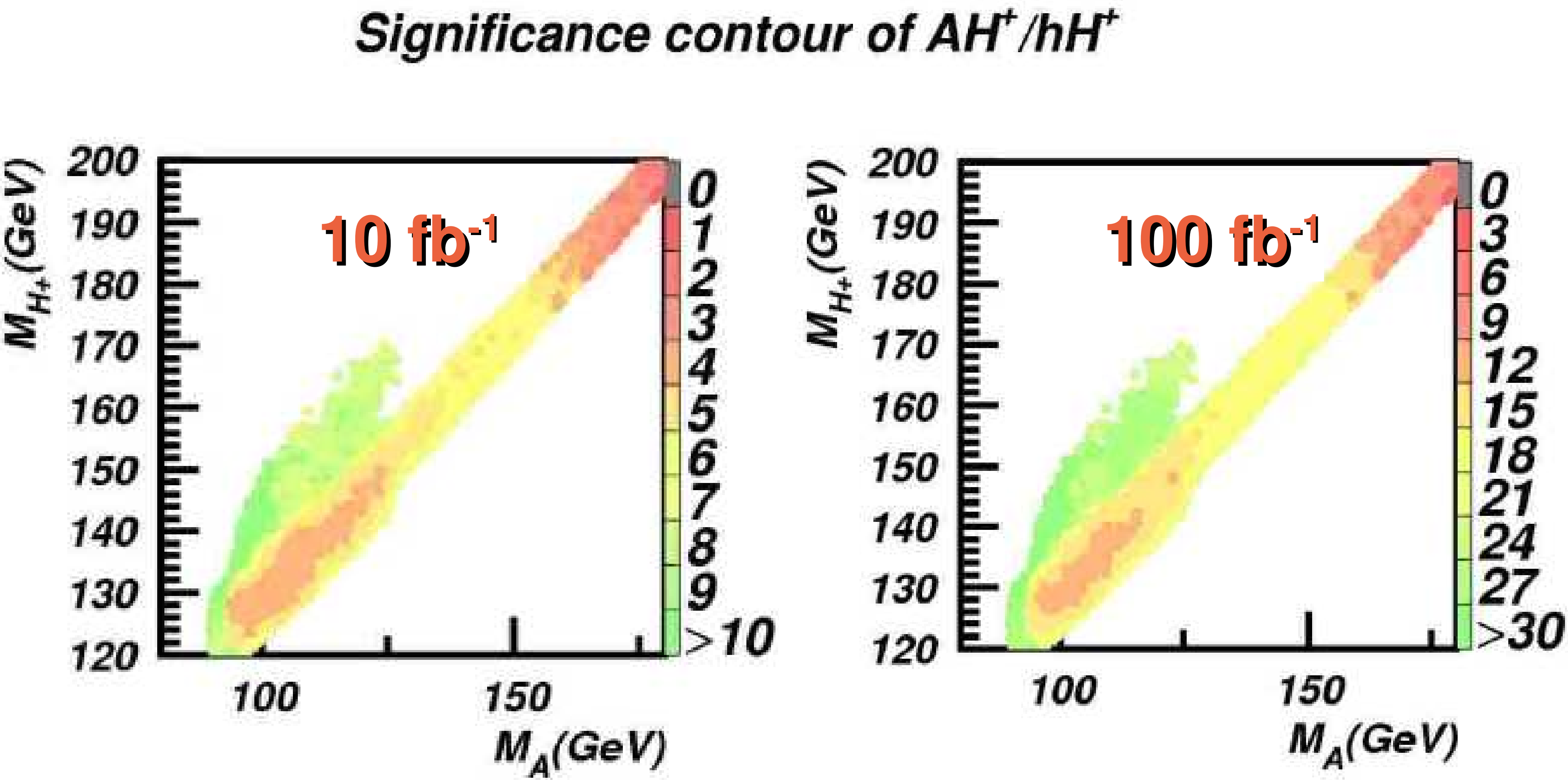
Higgs masses and their correlations in LHS



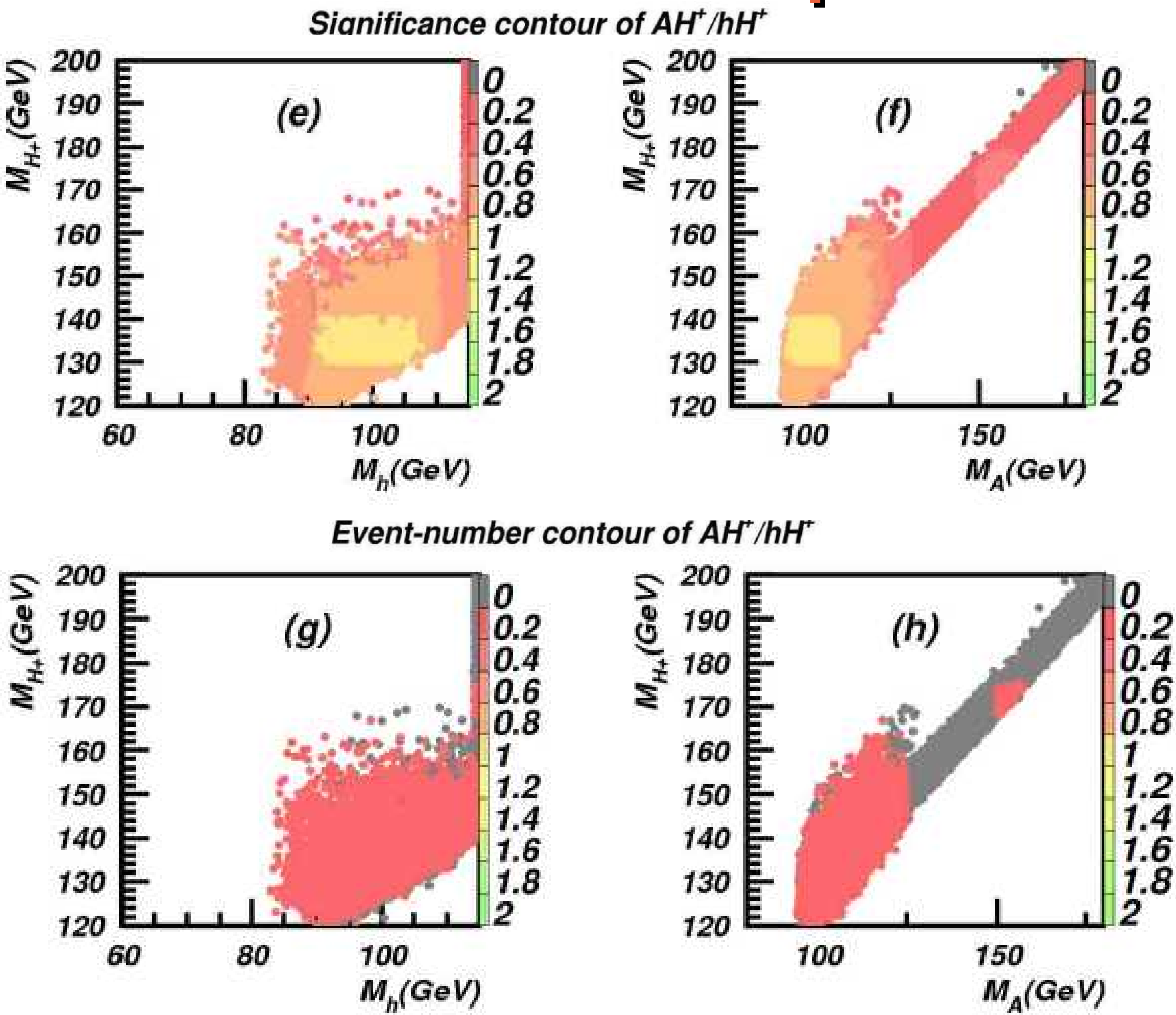
Higgs masses and their correlations in LHS



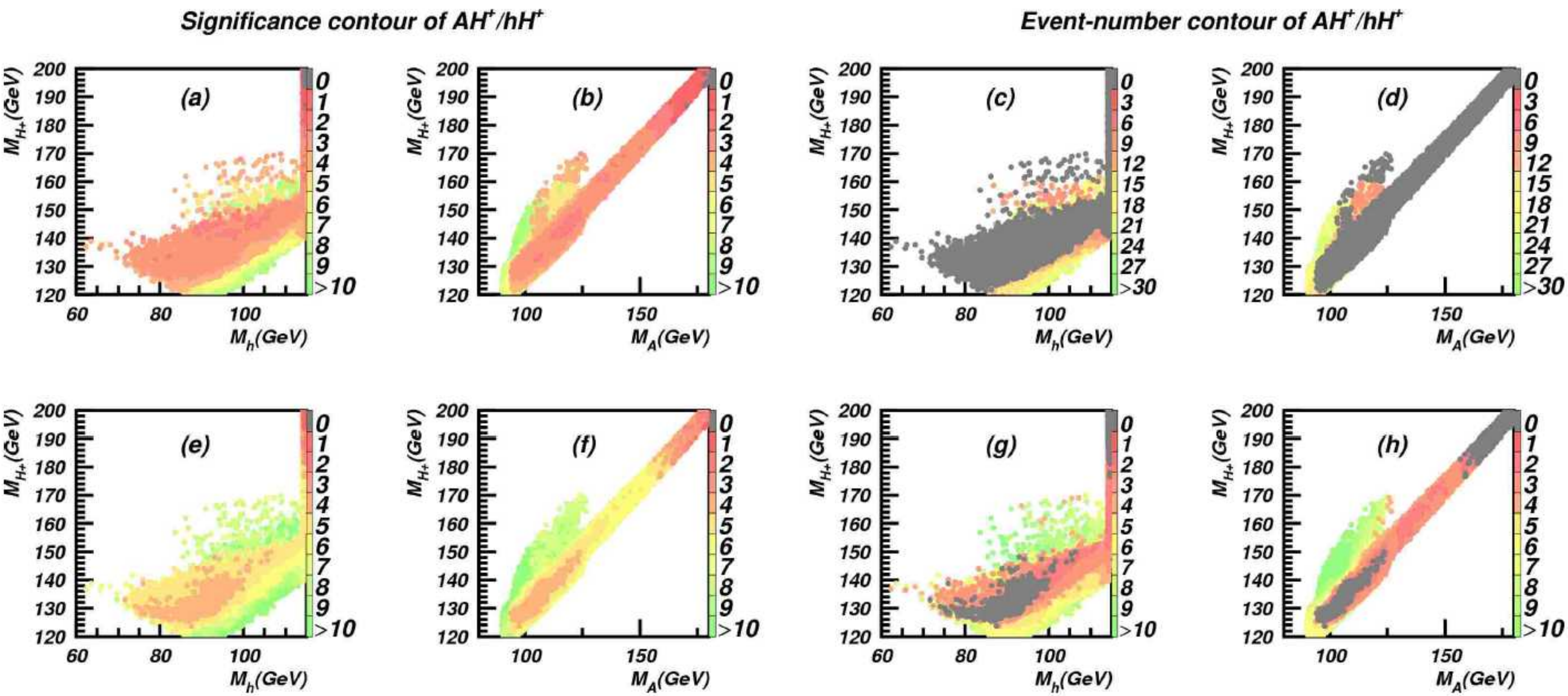
10 fb^{-1} and 100 fb^{-1} LHC reach for $H^{+}A$ production



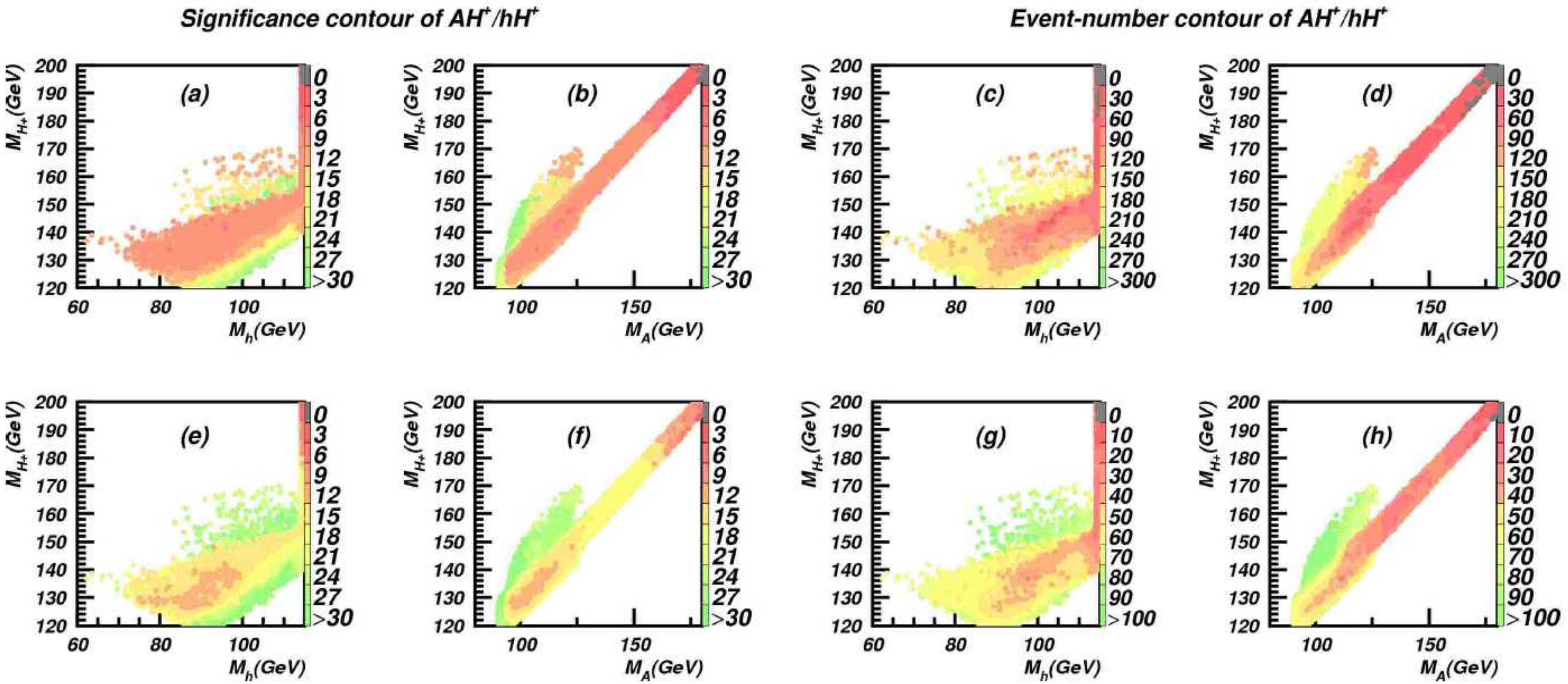
Tevatron reach for H^+A production



$10\ fb^{-1}$

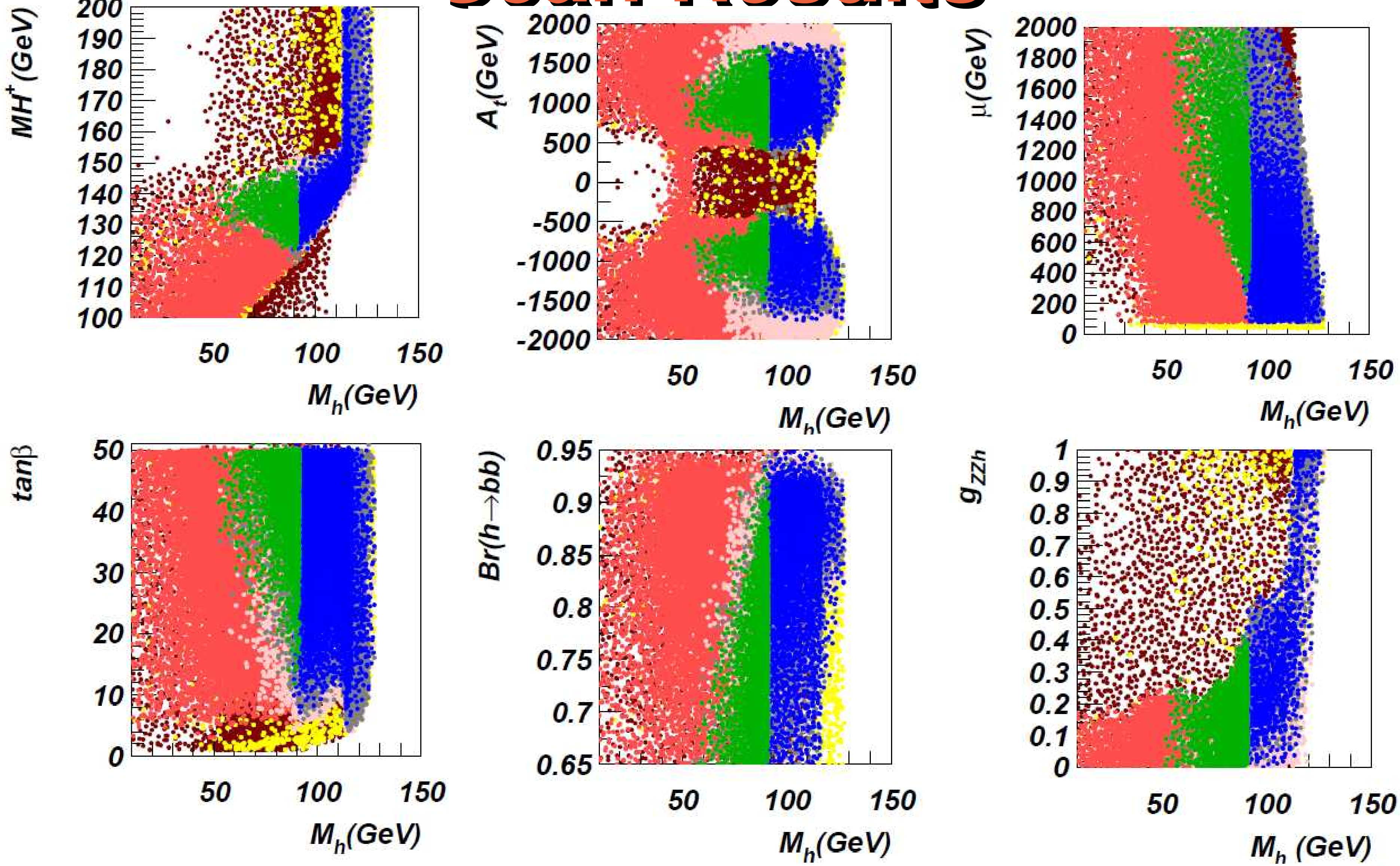

Significance contour of AH+/hH+
Event-number contour of AH+/hH+
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
M_H+(GeV)
M_h(GeV)
M_A(GeV)
>10
>30

100 fb^{-1}



Significance contour of AH+/hH+
Event-number contour of AH+/hH+
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
MH+(GeV)
Mh(GeV)
MA(GeV)

Scan Results



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