Limits and Outer Limits of the LEP Searches[1]

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Princeton

Aspen Winter Conference 2004

[1] P.W. Higgs, Phys. Lett. **12** (1964) 132;
F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321;
"The Outer Limits" circa **1963-1965**, MGM studios.

Theory of the Electroweak Interaction

Two Primordial Gauge Interactions:

$$\partial_\mu \rightarrow \partial_\mu + ig'\frac{Y}{2}B_\mu + igT_iW_\mu^i$$

Hypercharge(Y)
$U(1)_Y$ Symmetry

$$\boxed{\begin{matrix} T=0 \\ Y=0 \end{matrix}} \quad B_\mu$$

Left-Handed Isospin(T)
$SU(2)_L$ Symmetry

$$\boxed{\begin{matrix} T=1 \\ Y=0 \end{matrix}} \quad \begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}$$

Y

T

Higgs Field
1-complex doublet

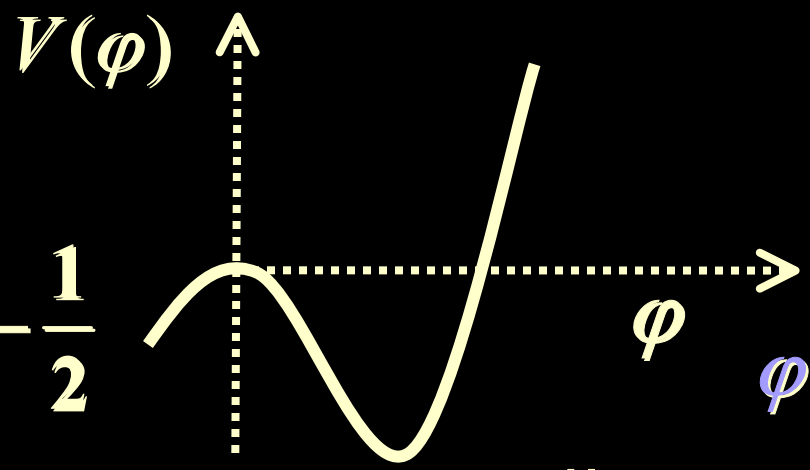
$$\boxed{\begin{matrix} T=\frac{1}{2} \\ Y=1 \end{matrix}} \quad \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{C} \begin{pmatrix} \bar{\varphi}^0 \\ -\varphi^- \end{pmatrix}$$

Properties of the Physical Vacuum

Self-Interacting Effective Potential:

$$V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4 \quad \text{(tree-level)}$$

Nature's Microscope



$$T_3\langle\varphi\rangle = -\frac{1}{2}$$

$$Y\langle\varphi\rangle = 1$$

$$\langle\varphi\rangle = \frac{\mu}{\sqrt{2\lambda}}$$

$$(Q = T_3 + \frac{Y}{2})\langle\varphi\rangle = 0$$

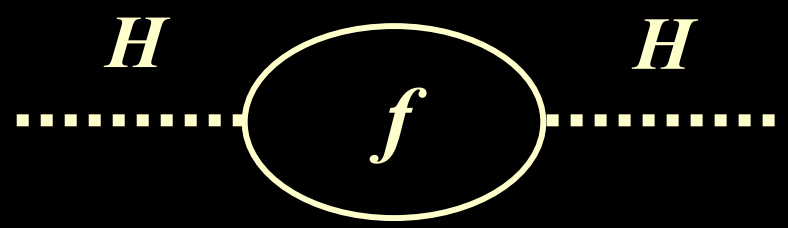
$$\varphi^{\pm}, \mathrm{Im}\{\varphi^0\} \Rightarrow W_L^{\pm}, Z_L$$

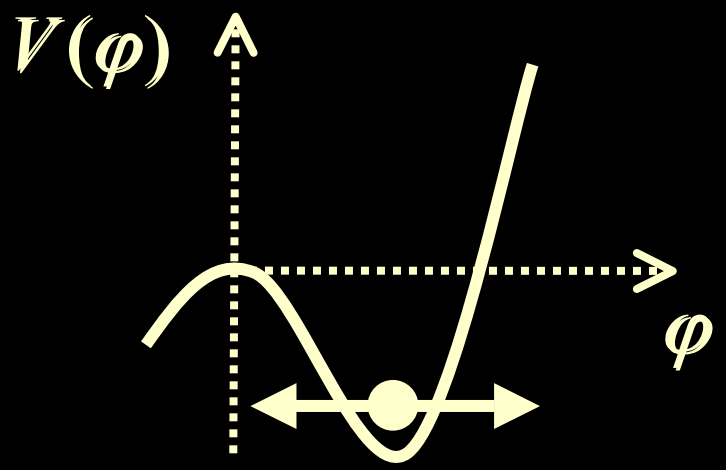
$$\mathrm{Re}\{\varphi^0\} \Rightarrow \langle\varphi\rangle + H$$

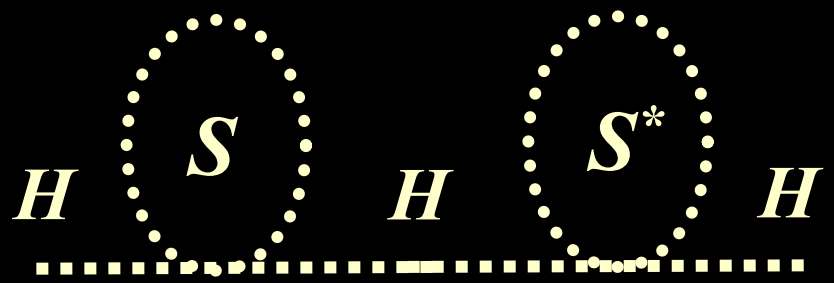
missing link

Stability of the Electroweak Scale

Self-Interacting Effective Potential:







Electroweak scale intimately tied to m_H

$$\Delta m_H^2 = \frac{1}{(4\pi)^2}\left(-2|\lambda_f|^2 + 2\lambda_S\right)\Lambda_{UV}^2 + \cdots \to 0$$

SUSY Higgs Sector

Down-type mass

$$m_d = \frac{y_d v_d}{\sqrt{2}}$$

Up-type mass

$$m_u = \frac{y_u v_u}{\sqrt{2}}$$

$$\boxed{v_u^2 + v_d^2 = v^2}$$

Electroweak Energy Scale

$$\boxed{\tan\beta = v_u / v_d}$$

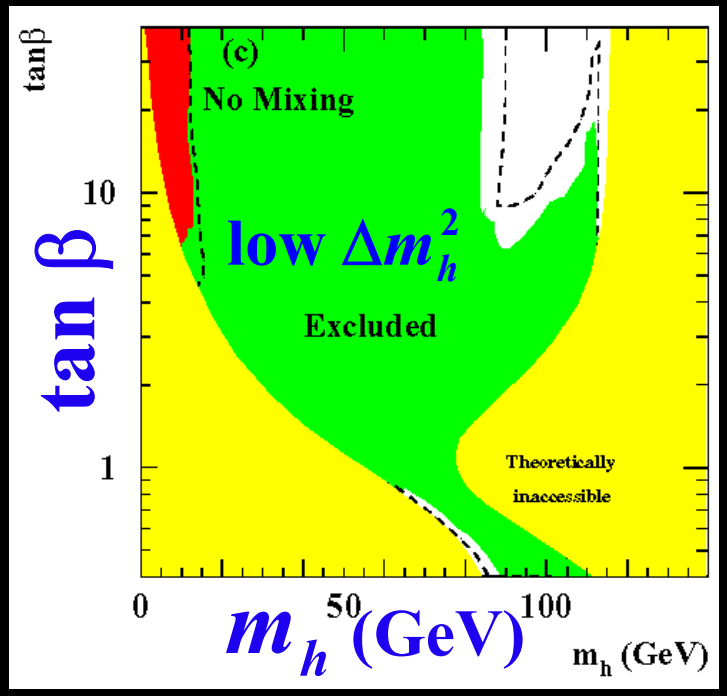
m_{top}/m_{bottom}?

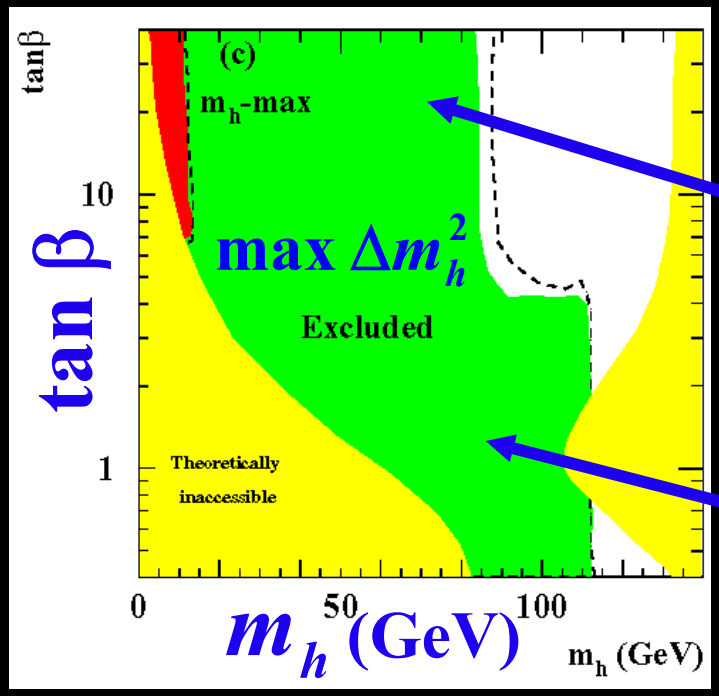
8 degrees of freedom

– 3 longitudinal polarizations ($W_L^{\pm}, Z_L$)

leaves 5 Higgs bosons: $h, H, A, H^{\pm}$

CP Conserving MSSM Searches





(high tanβ)

$e^+e^- \to hA$

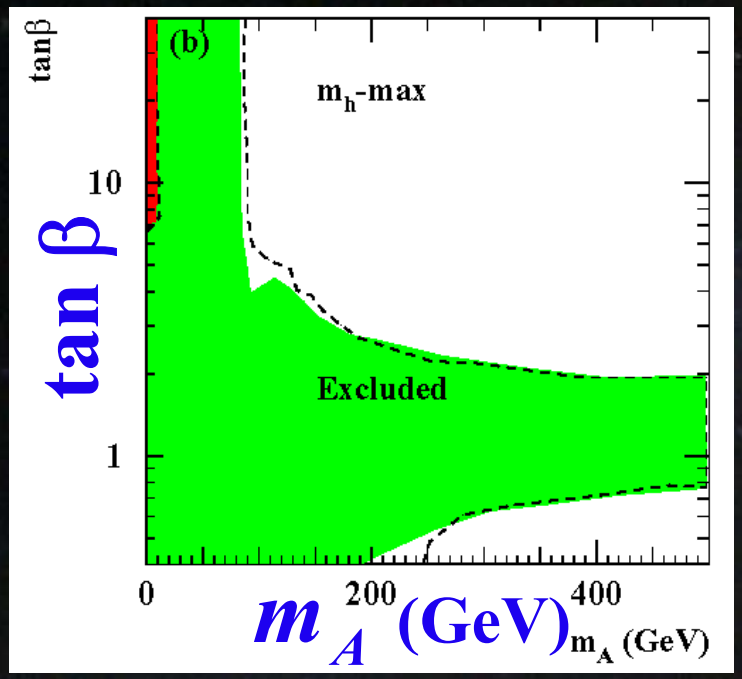
(low tanβ)

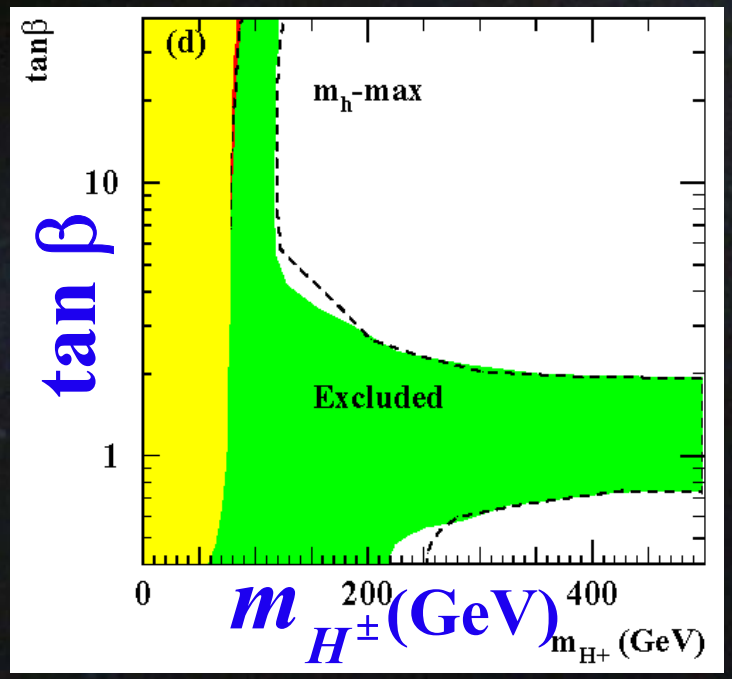
$e^+e^- \to hZ$

Mass of lightest Higgs boson (CP-even h): $m_h \leq m_Z$ (tree-level)

$$\Delta m_h^2 \approx \frac{N_c}{4\pi^2} y_t^2 v^2 \sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

CP Conserving MSSM Searches





Other physical Higgs bosons in two-doublet model:

$$A \text{ (CP-odd)} : m_A^2 = 2\mu^2 + \cdots$$

$$H^\pm : m_{H^\pm}^2 = m_W^2 + m_A^2$$

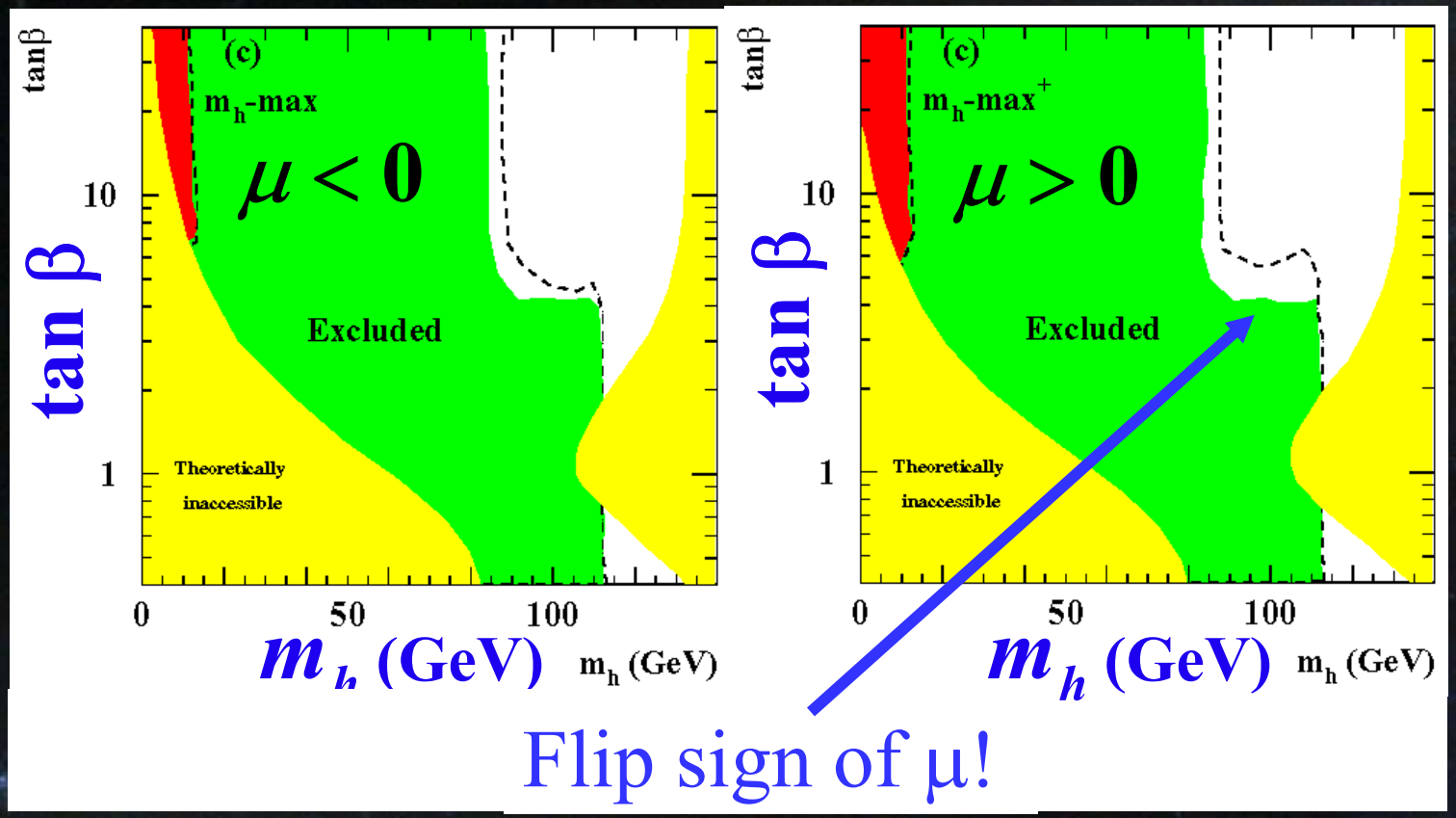
$$H \text{ (CP-even)} : m_H > m_h$$

For large μ

$$m_H \approx m_{H^\pm} \approx m_A$$

Decoupling limit

CP Conserving MSSM Searches

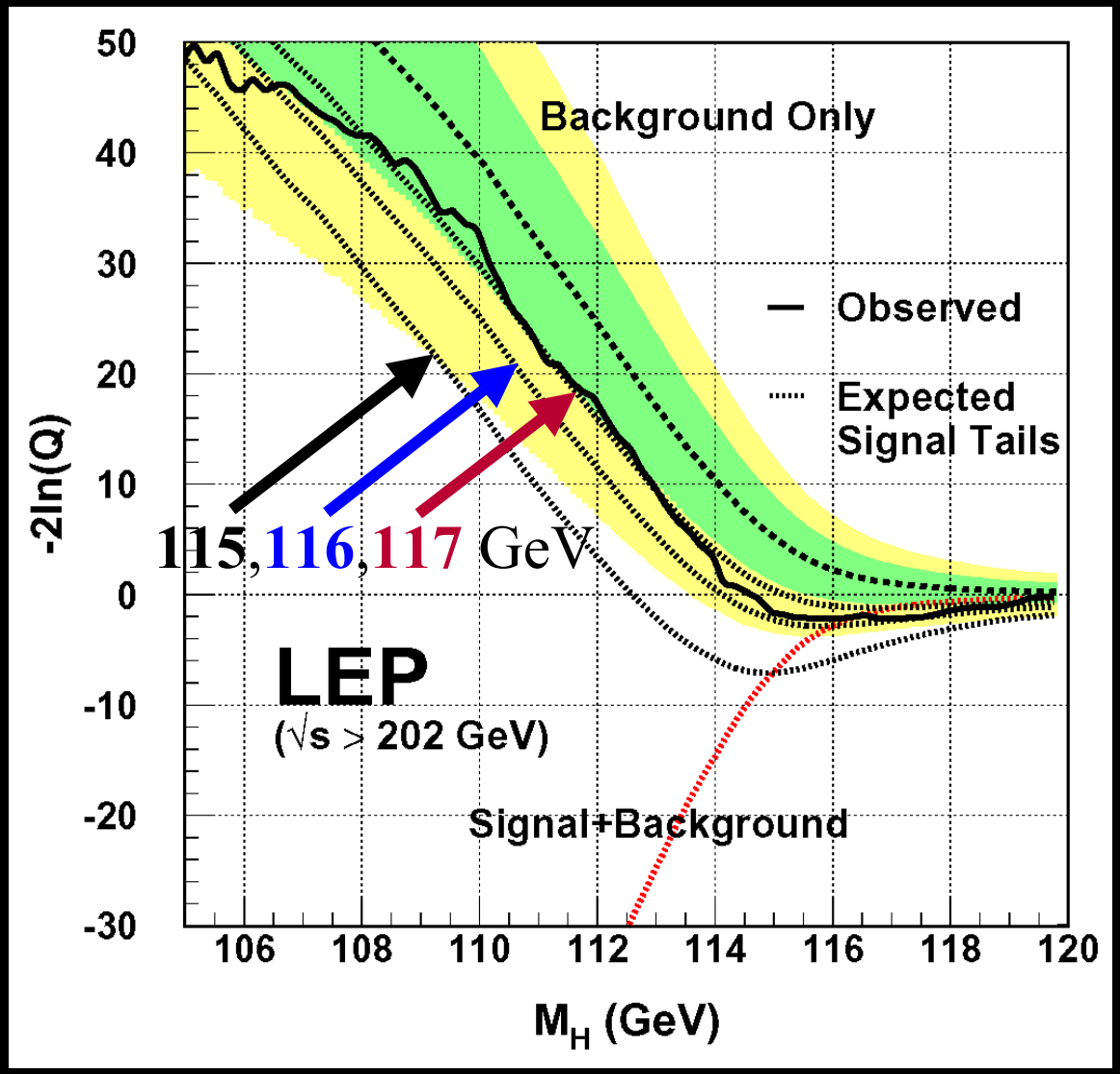


Flip sign of μ!

Superpotential: $W = \mu \hat{H}_u \hat{H}_d$

$$|\mu| = M_2 = 200\,\text{GeV}$$
$$m_{SUSY} = 1\,\text{TeV}$$

Standard Model Higgs Search



Very Slight Excess Compatible with Predicted Rates above:

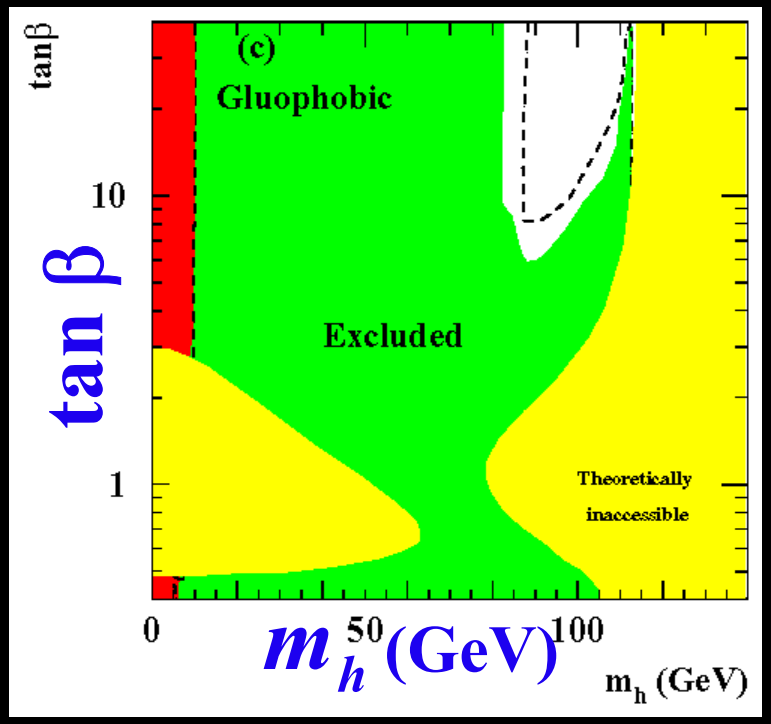
$$m_H > 116\ \mathrm{GeV/c^2}$$

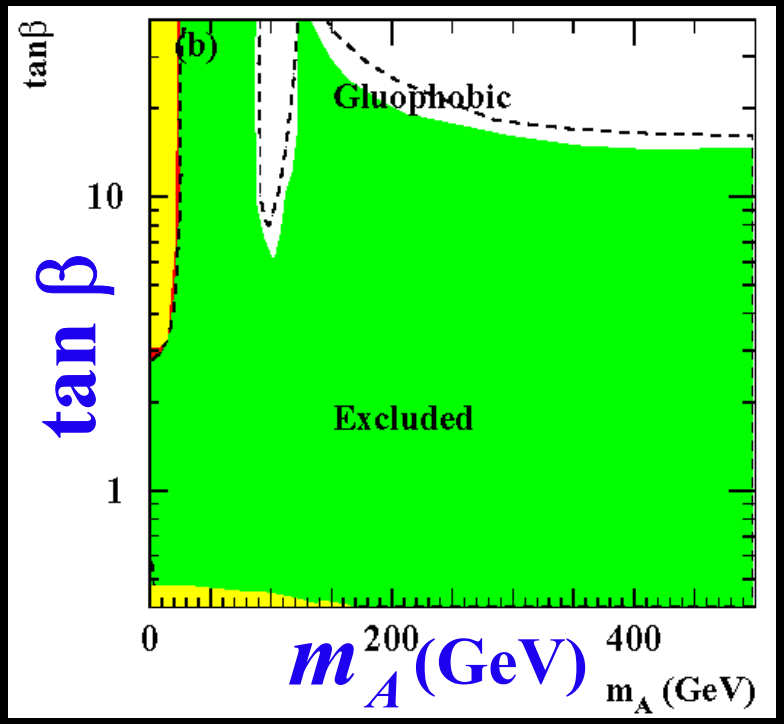
Lower Limit Set at CL=95%:

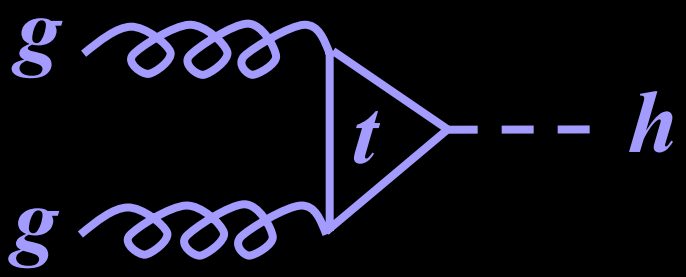
$$m_H > 114.4\ \mathrm{GeV/c^2}$$

Excluded down to Zero mass

CP Conserving MSSM Searches







Pave the way to the LHC…

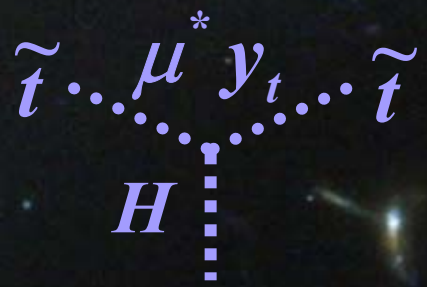
SUSY Higgs Sector and $\not{C}\not{P}$

Non-gauge interactions from superpotential:

$$W = \hat{U} y_u \hat{Q} \hat{H}_u - \hat{D} y_d \hat{Q} \hat{H}_d - \hat{E} y_e \hat{L} \hat{H}_d$$

Add Soft SUSY Breaking Terms $\left(\text{all} \propto m_{soft} \right)$

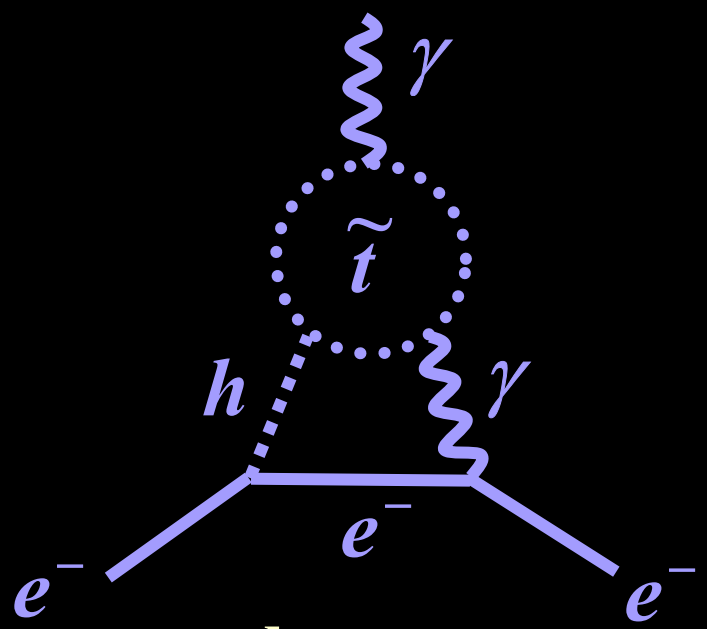
$$\Delta V = \tilde{U} A_u y_u \tilde{Q} H_u - \tilde{D} A_d y_d \tilde{Q} H_d - \tilde{E} A_e y_e \tilde{L} H_d$$



$\not{C}\not{P}$ **Terms** $\propto \text{Im}\{\mu A_t\}$

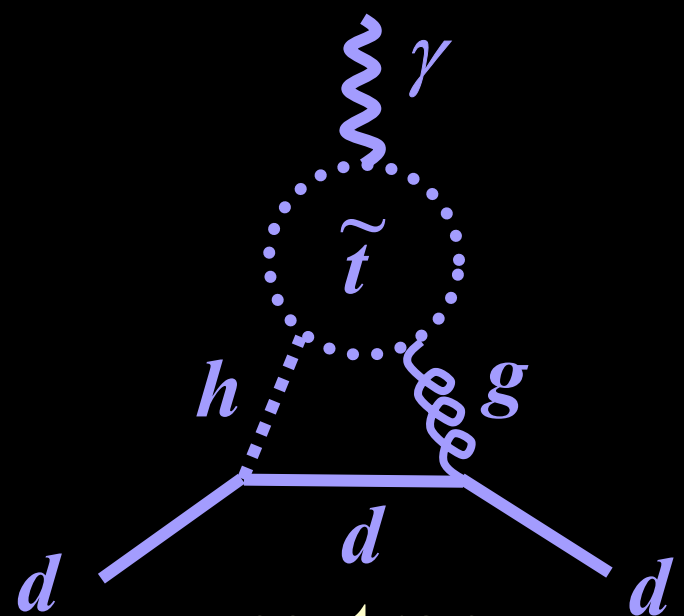
Electronic Dipole Moment Limits

Barr-Zee-type EDM Diagrams: $|d| \propto \frac{m_f}{m_h^2}$



electron

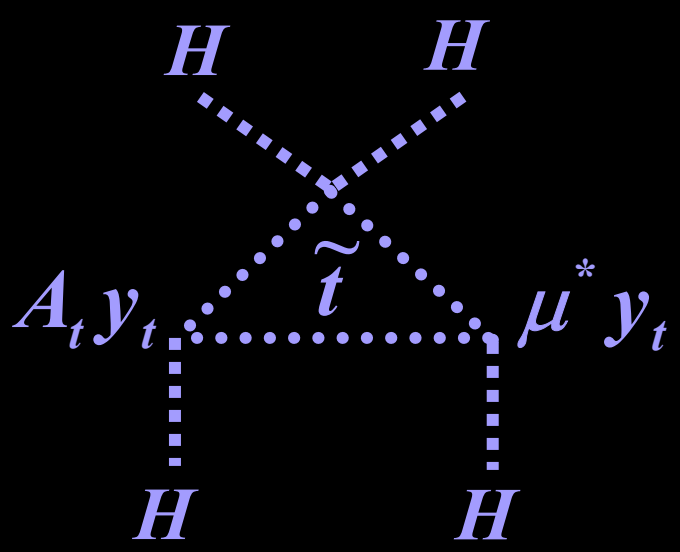
$$|d_e| < 4 \times 10^{-27}\, ecm$$



neutron

$$|d_n| < 6 \times 10^{-26}\, ecm$$

SUSY Higgs Sector and $\not{C}\not{P}$



$\not{C}\not{P}$ **Terms** $\propto \mathrm{Im}\{\mu A_t\}$

***h, H* (CP-even)**

***A* (CP-odd)**

H_1, H_2, H_3

$e^+e^- \to hA$

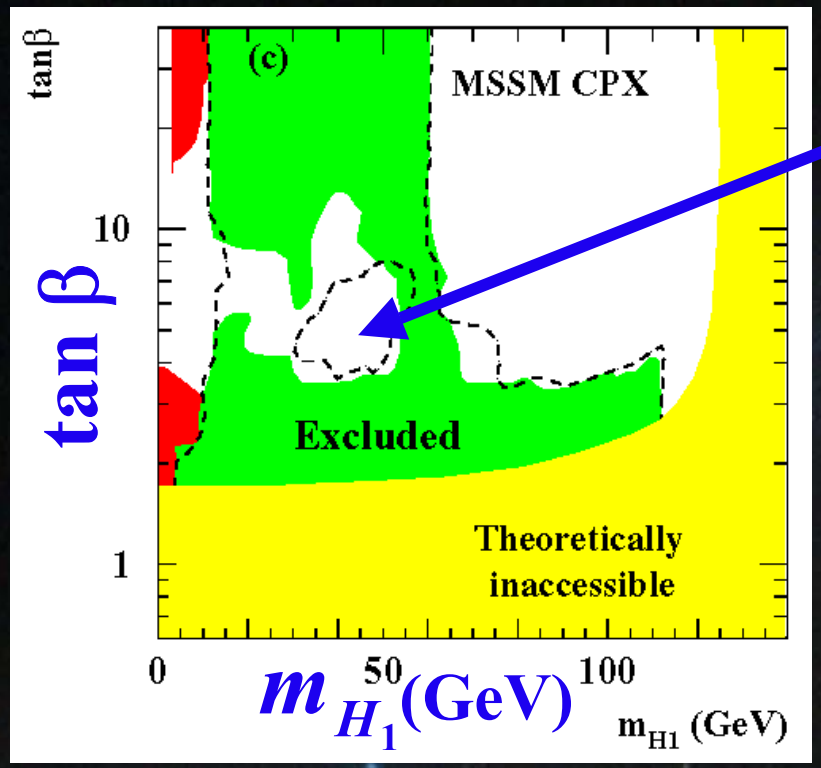
$e^+e^- \to hZ$

$e^+e^- \to H_1 H_2$

$e^+e^- \to H_1 Z$

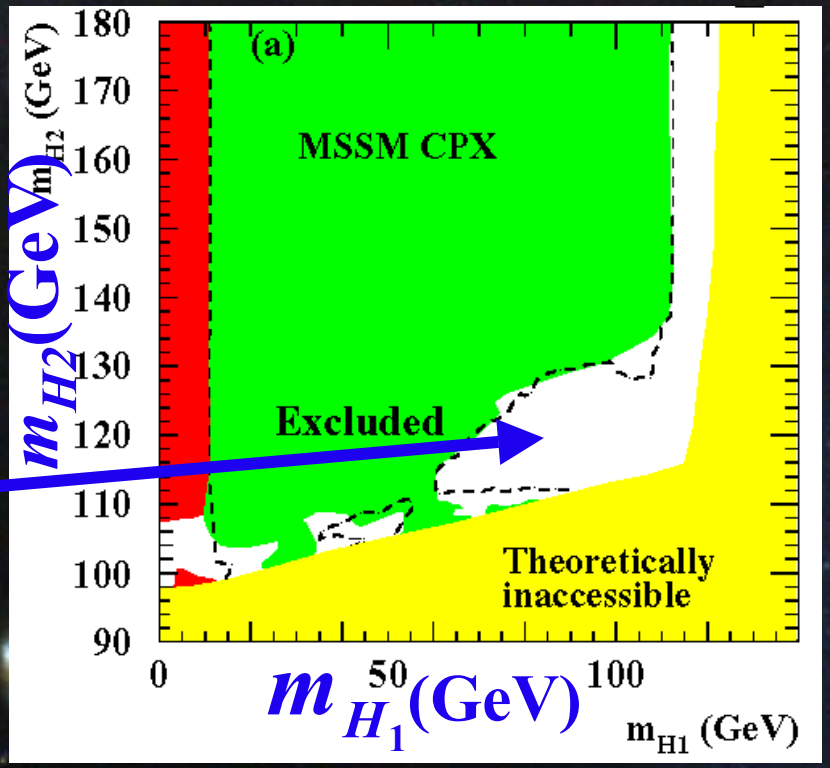
$e^+e^- \to H_2 Z$

CP Violating MSSM Searches



Low Mass Region opens up

$$e^+e^- \to H_2 Z$$
$$H_2 \to H_1 H_1$$

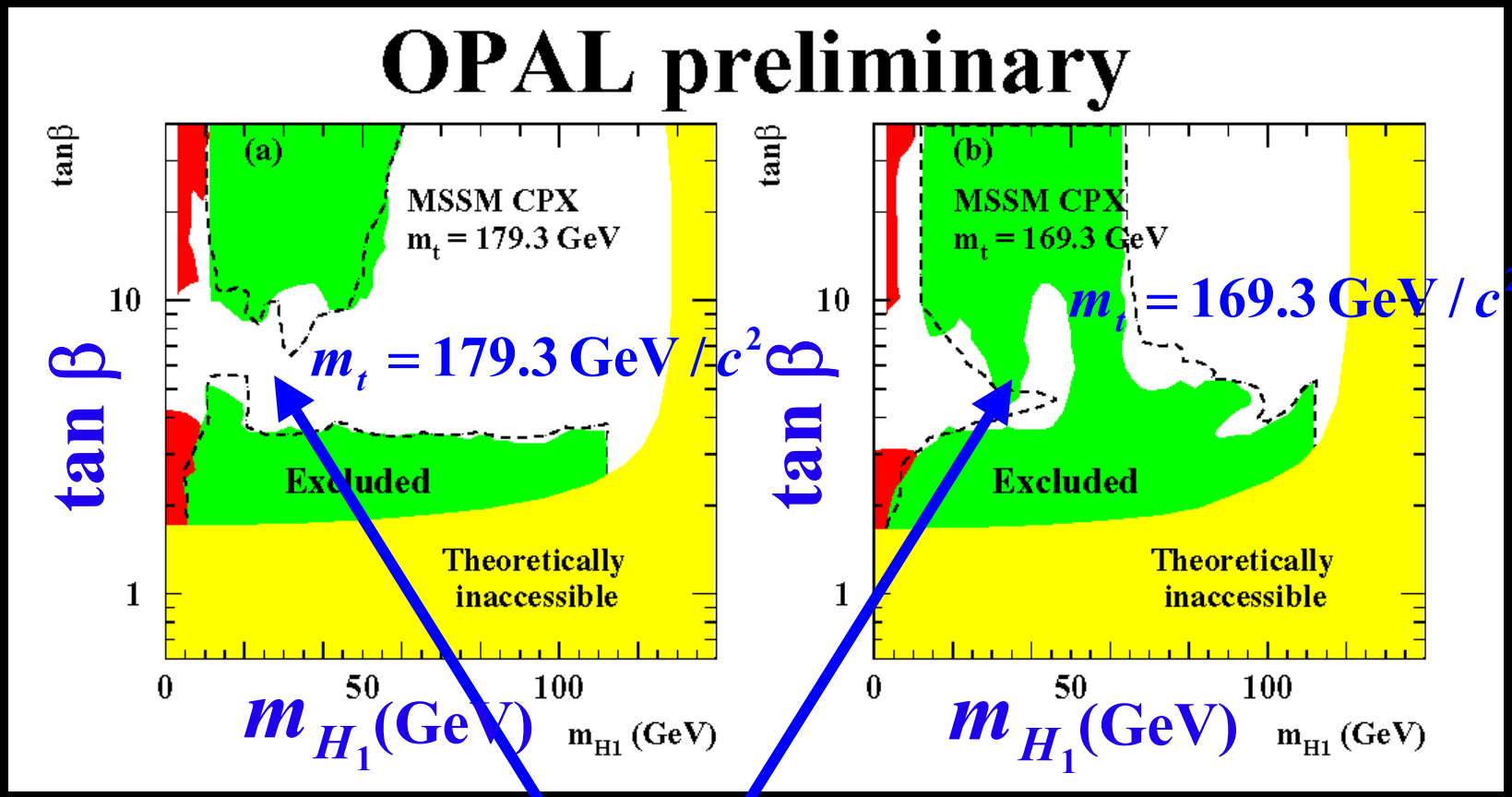


"Sum Rule"-loss from

$$e^+e^- \to H_1 Z$$

$$e^+e^- \to H_2 Z$$

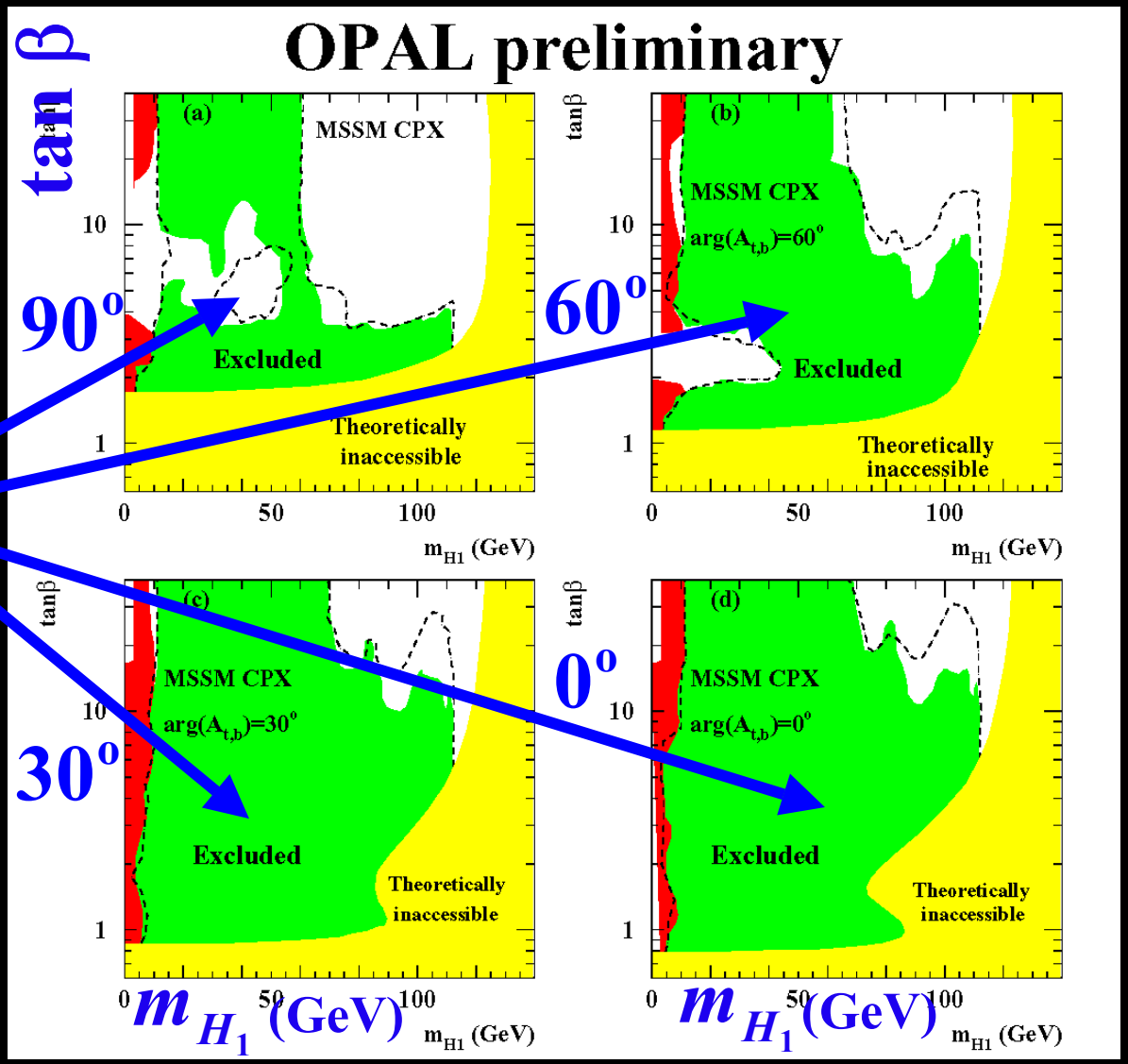
CP Violating MSSM Searches



Exclusion Region Sensitive to Top Mass

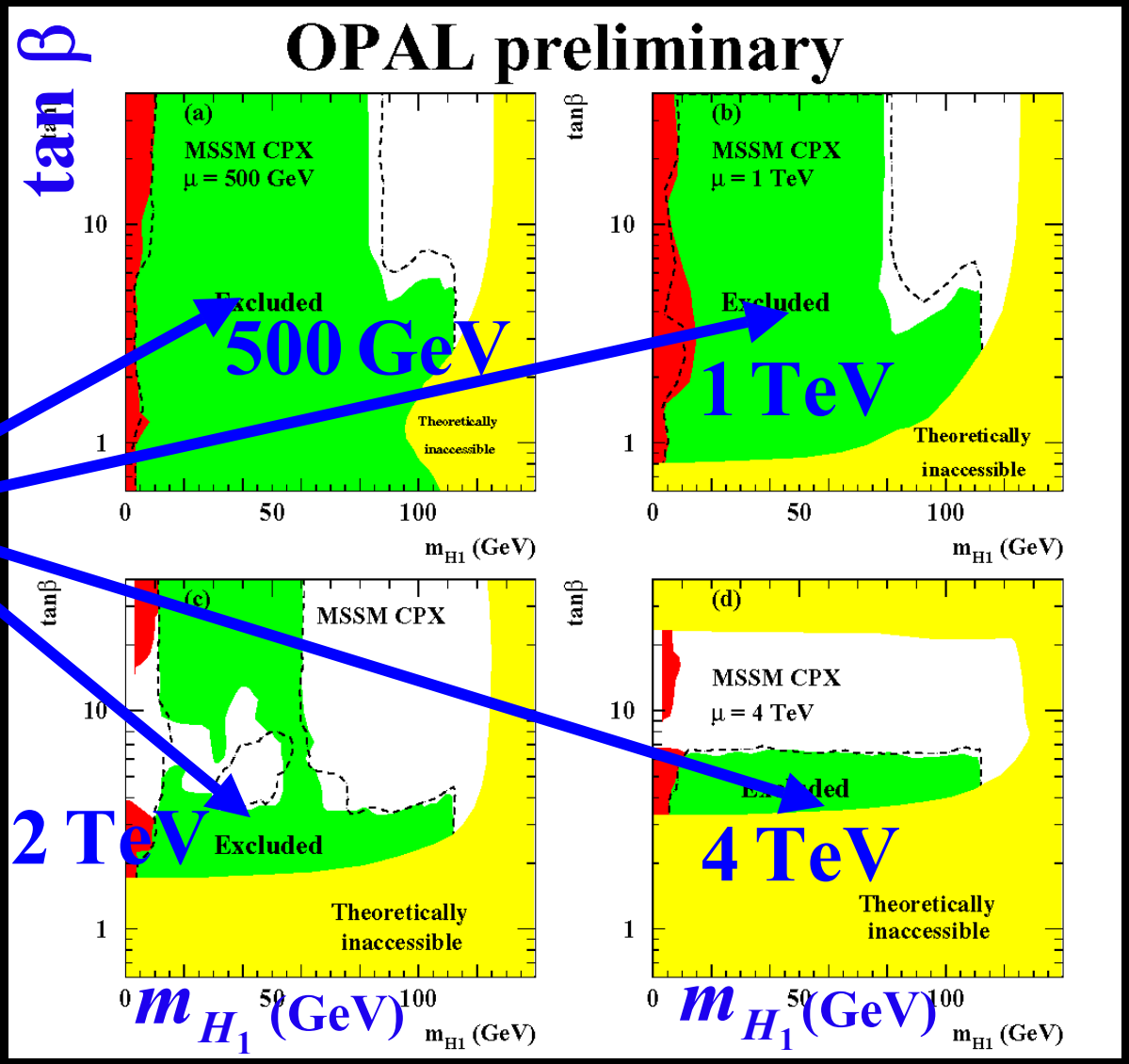
CP Violating MSSM Searches

Sensitive to
$\not{CP}$ phase



CP Violating MSSM Searches

Sensitive to
μ–parameter



General Two-Doublet Searches

Fermion ⇔ One Doublet
To Avoid Flavor-Changing Neutral Currents

***Type* II *Models*:** **One Up-Type Doublet**
One Down-Type Doublet

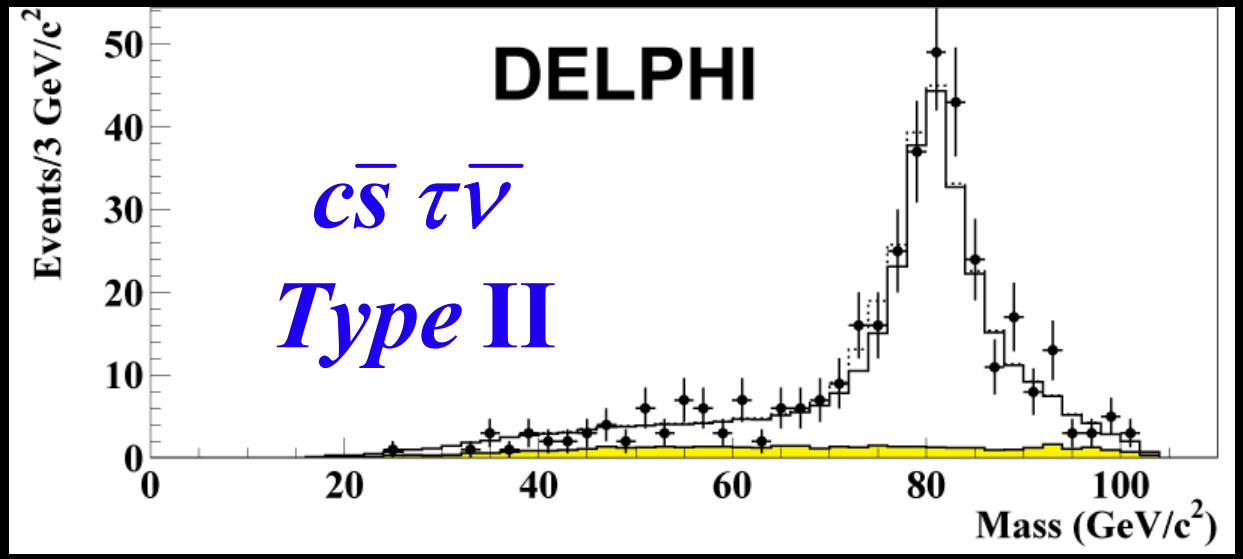
***Type* I *Models*:** **One Doublet for all Fermions**

$$e^+e^- \to hZ \;:\quad \sigma_{hZ} = \sin^2(\beta-\alpha)\,\sigma_{hZ}^{SM}$$

$$e^+e^- \to hA \;:\quad \sigma_{hZ} = \cos^2(\beta-\alpha)\,\overline{\lambda}\,\sigma_{\nu\bar{\nu}}^{SM}$$

$$e^+e^- \to H^+H^-$$

Singly-Charged Higgs Searches



$$e^+e^- \to H^+H^-$$

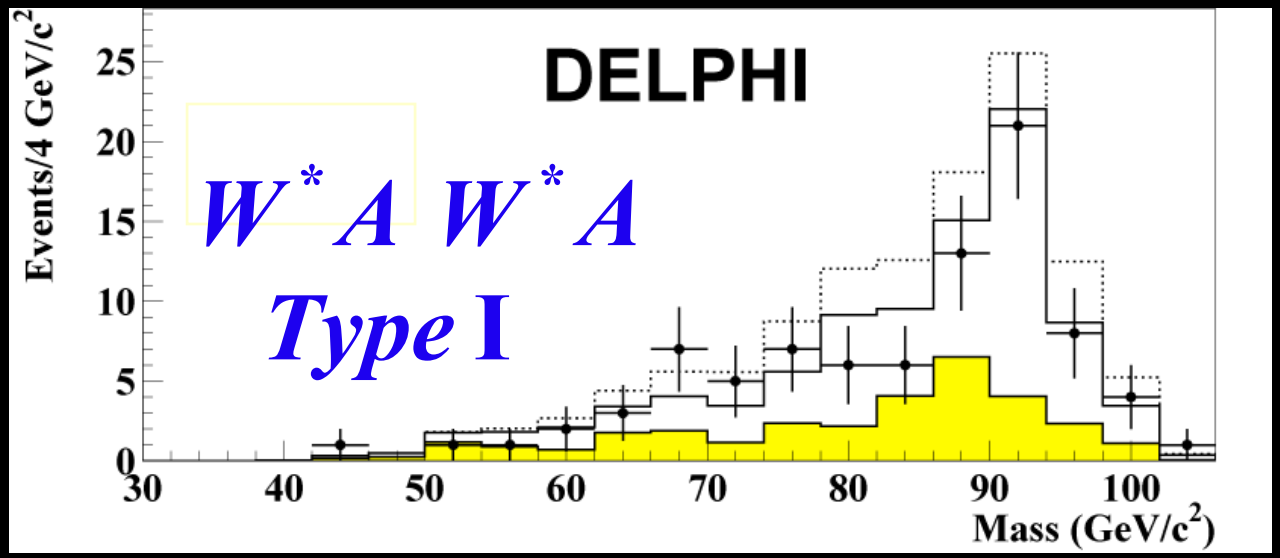
Fermion Couplings

$$H^+ \to c\bar{s}$$

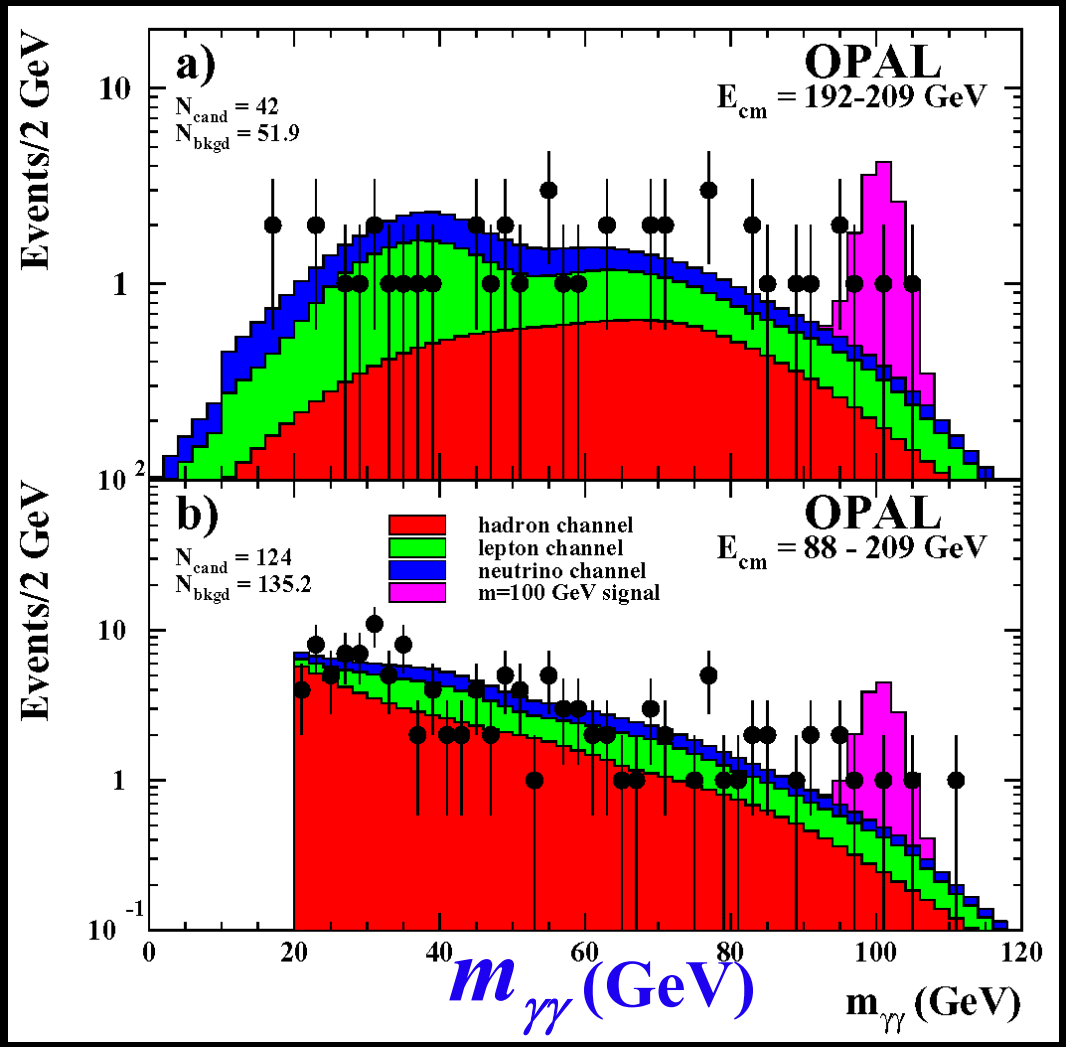
$$H^- \to \tau\bar{\nu}$$

$$H^- \to W^* A$$

$$A \to b\bar{b}$$



Fermiophobic Searches

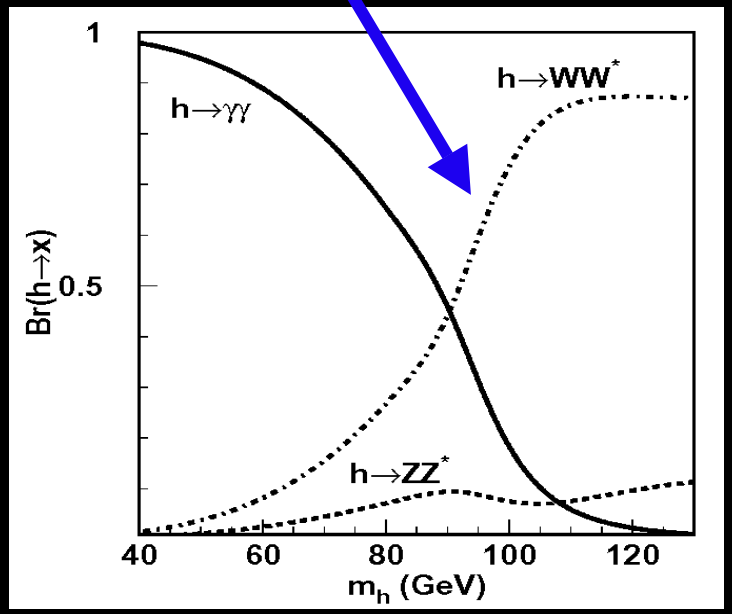


$$e^+e^- \rightarrow hZ$$

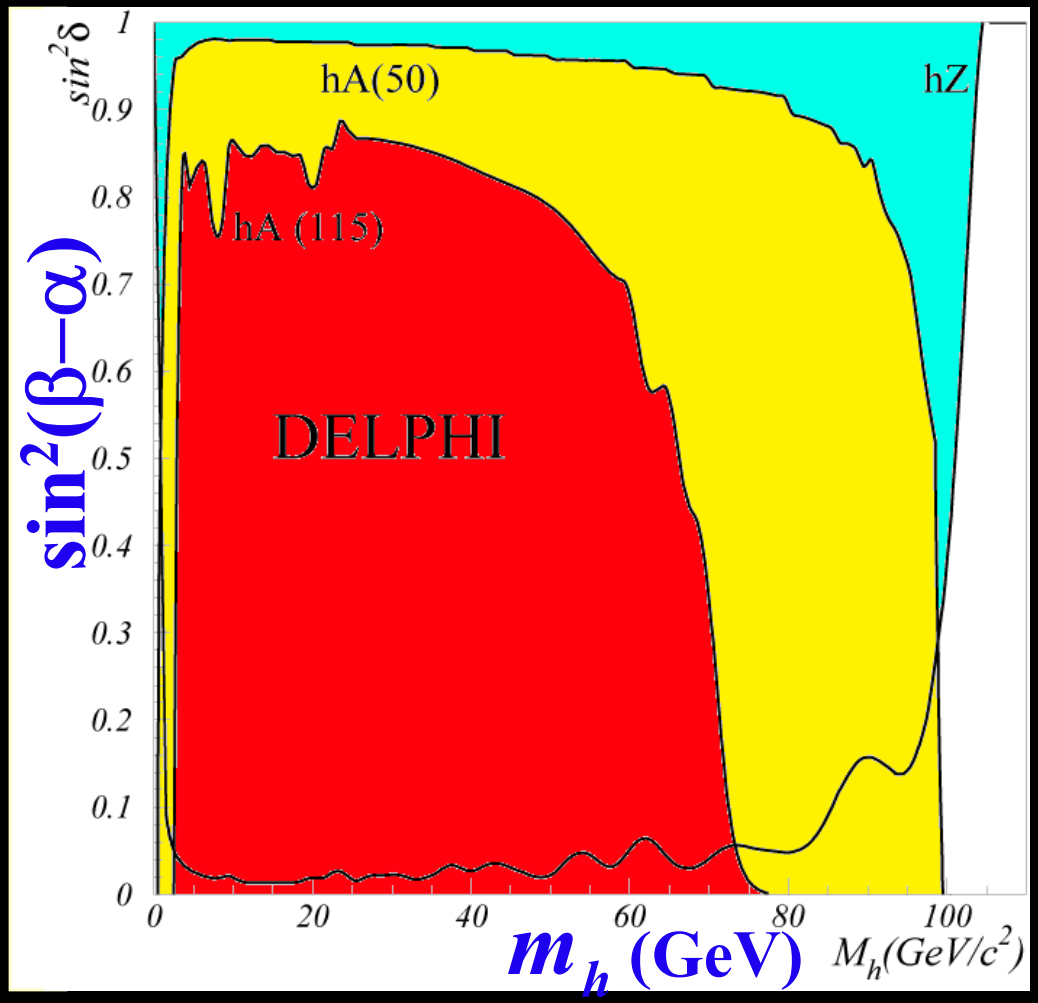
Boson Couplings

$$h \rightarrow \gamma\gamma$$

$$h \rightarrow WW^* \text{ and } ZZ^*$$



Fermiophobic Searches



Higgsstrahlung and Pair Production

$$e^+e^- \to hZ \propto \sin^2(\beta-\alpha)$$

$$e^+e^- \to hA \propto \cos^2(\beta-\alpha)$$

Decay Modes:

$$h \to \gamma\gamma$$

$$A \to b\bar{b}$$

Left-Right Higgs Sector

Beauty and Consequence

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\hat{Q}_R = \begin{pmatrix} \hat{U} \\ \hat{D} \end{pmatrix} \sim (3,1,2,\frac{1}{3}) \quad \hat{L}_R = \begin{pmatrix} \hat{\nu} \\ \hat{E} \end{pmatrix} \sim (1,1,2,-1)$$

Charge Operator for $U(1)_{\text{em}}$

$$Q = T_{3L} + T_{3R} + \frac{1}{2}(B - L)$$

$$\hat{\Phi} = \begin{pmatrix} H_u^0 & H_u^+ \\ H_d^- & H_d^0 \end{pmatrix} \rightarrow \begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}$$

Triplet Field
w/ Doubly-Charged
Higgs Boson

$$\hat{\Delta}_{L,R} = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_{L,R}^- & \Delta_{L,R}^0 \\ \Delta_{L,R}^{--} & -\frac{1}{\sqrt{2}}\Delta_{L,R}^- \end{pmatrix} \rightarrow \begin{pmatrix} 0 & v_R \\ 0 & 0 \end{pmatrix}$$

See-saw Mechanism

Strong Restriction on Left-Handed Triplets in Standard Model: $v_L < 9\,\text{GeV}$

(tree-level) $\rho = m_W^2 / \cos^2\theta_W m_Z^2 = 0.9998 \pm 0.0008$

No Restriction on v_R

$W = y_\Phi \hat{\Psi}_L \hat{\Phi} \hat{\Psi}_R$ **Normal doublet Left $\Leftrightarrow$ Right**

$+ y_{\Delta_L} \hat{\Psi}_L \hat{\Delta}_L \hat{\Psi}_L + y_{\Delta_R} \hat{\Psi}_R \hat{\Delta}_R \hat{\Psi}_R$

Triplet Left $\Leftrightarrow$ Left and Right $\Leftrightarrow$ Right (only leptons)

Mass Scale of $SU(2)_R \times U(1)_{B\text{-}L}$ Breaking

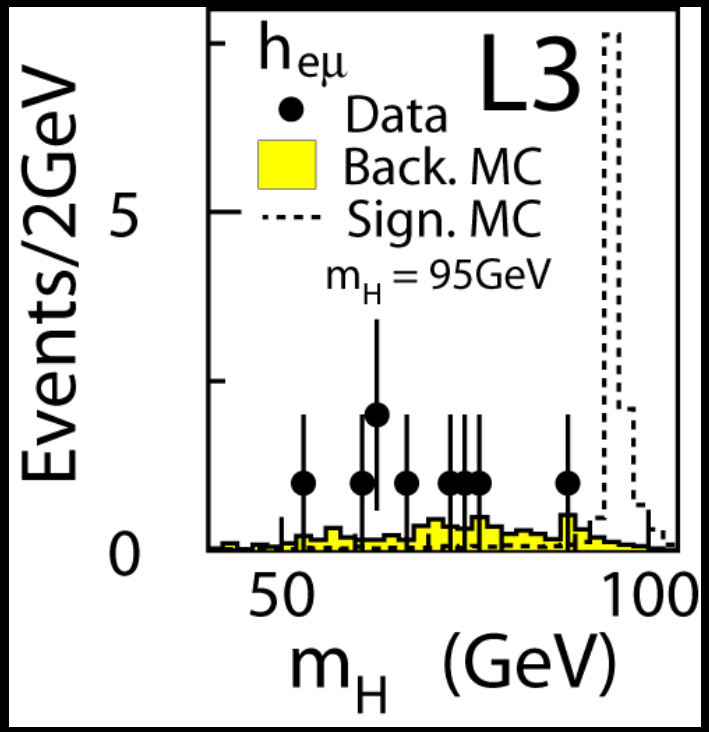
If Δ_R acquires v_R, then $m_{\nu_R} \approx m_R$

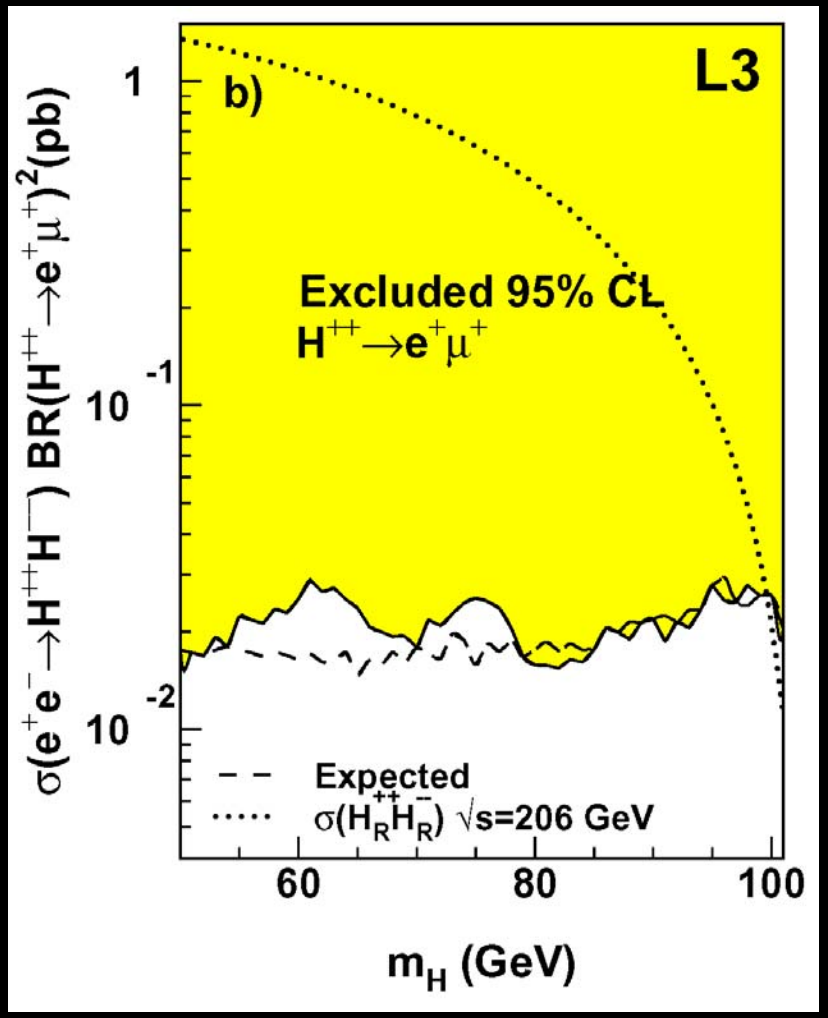
and $m_{\nu_L} \approx m_D^2 / m_R \approx 0.06\,\text{eV}/c^2$ (see-saw)

Doubly-Charged Higgs Searches

$$e^+e^- \rightarrow \Delta_R^{++}\Delta_R^{--} \text{ or } \Delta_L^{++}\Delta_L^{--}$$

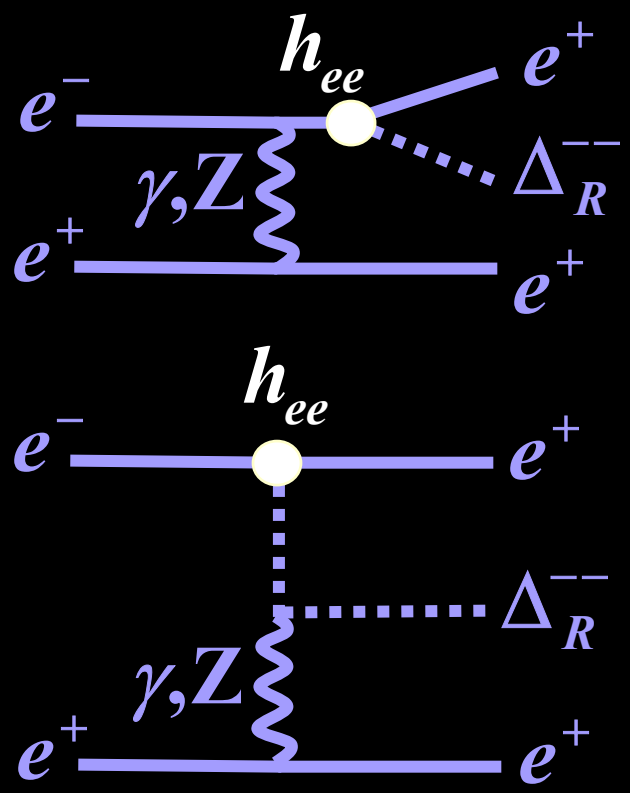
$$\Delta_R^{\pm\pm} \rightarrow e^\pm\mu^\pm$$

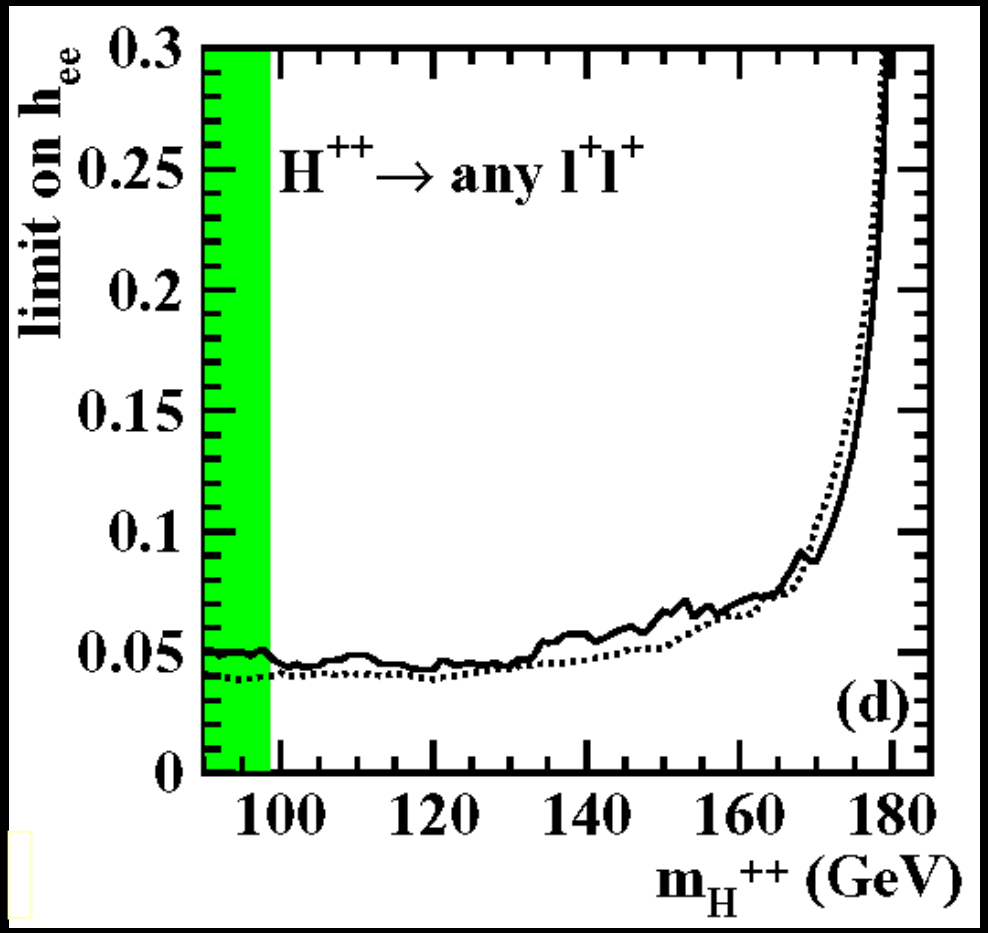




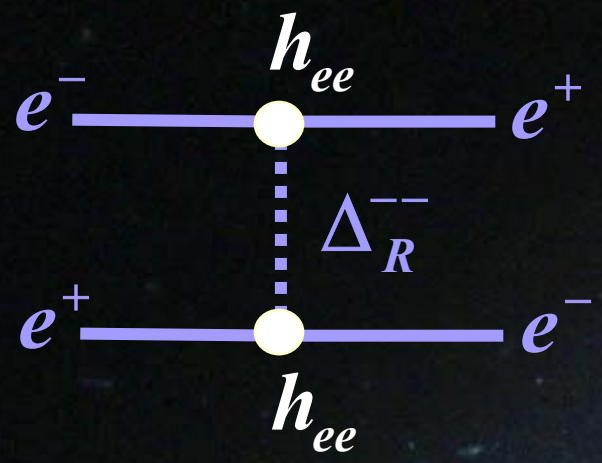
Doubly-Charged Higgs Searches

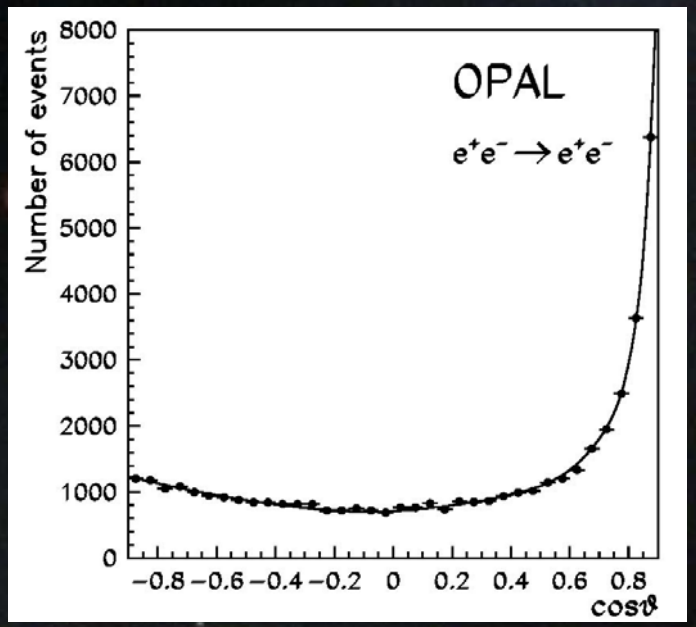
$$e^+e^- \rightarrow \Delta_R^{\pm\pm} e^{\mp} e^{\mp}$$

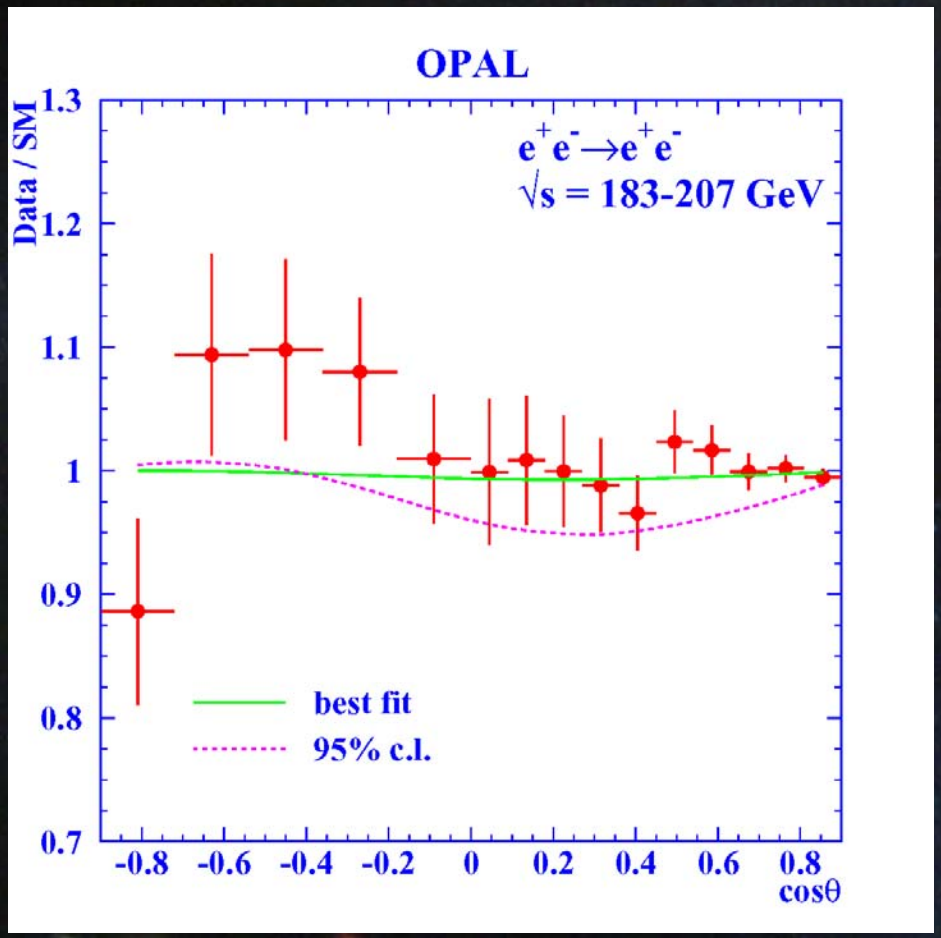




Doubly-Charged Higgs Searches







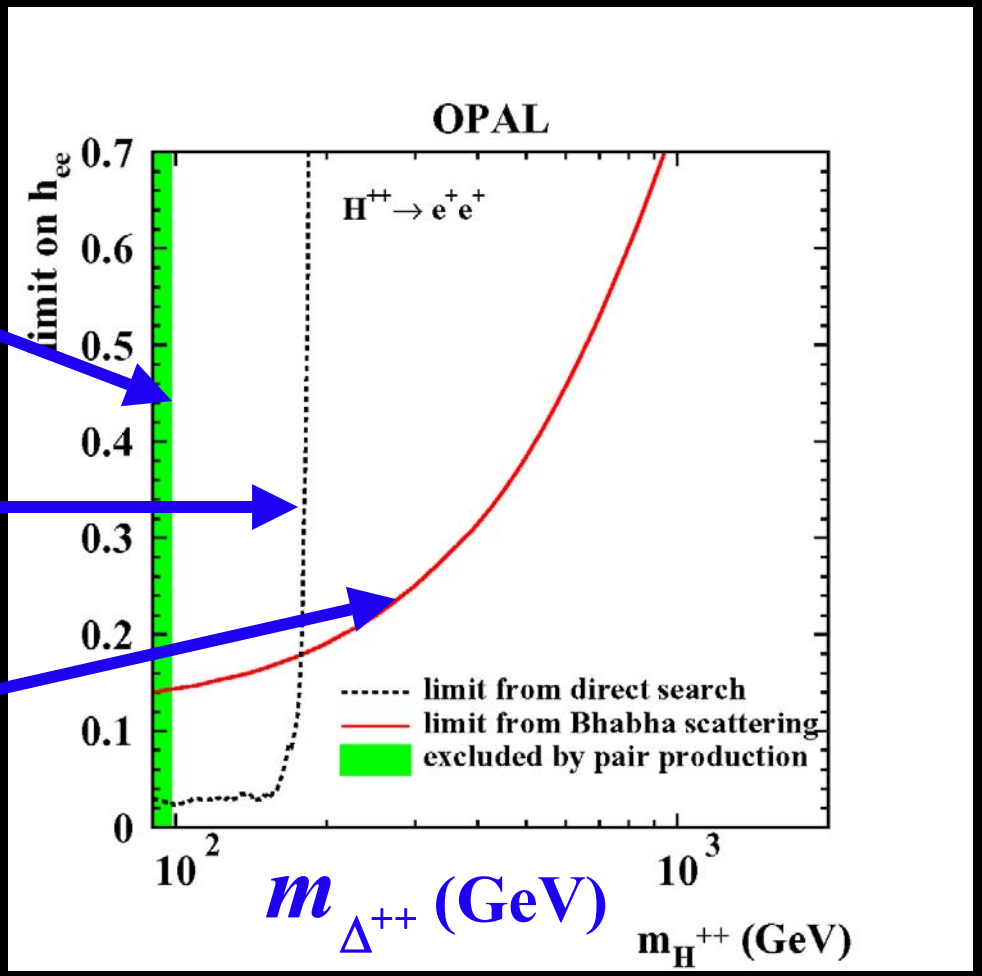
Doubly-Charged Higgs Searches

$\Delta^{++}_{R,L}$ **Limits**

Pair Production

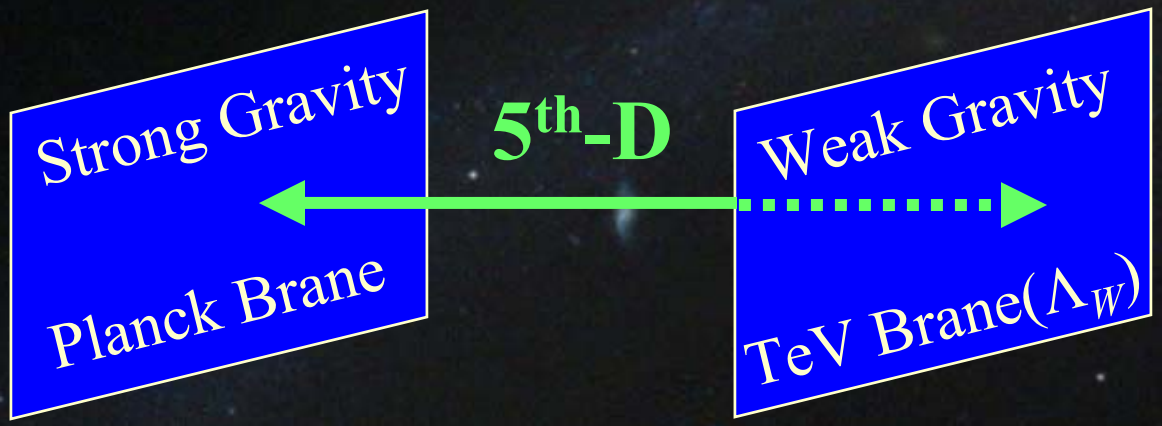
Single Production

Bhabha Scattering



Radion-Higgs Sector Mixing

Local fluctuation of Inter-brane distance: $r_0 \to r_0 + \Delta r(x)$

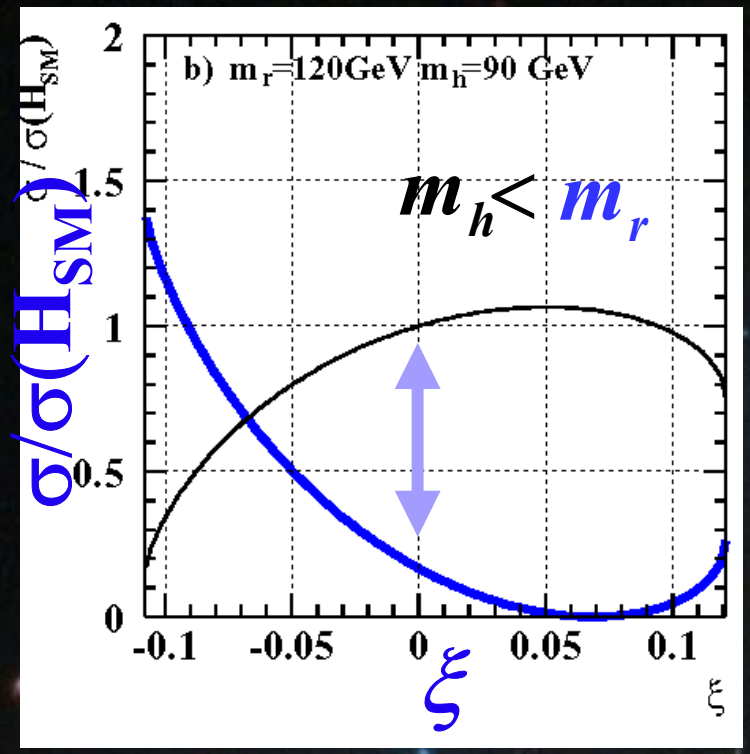


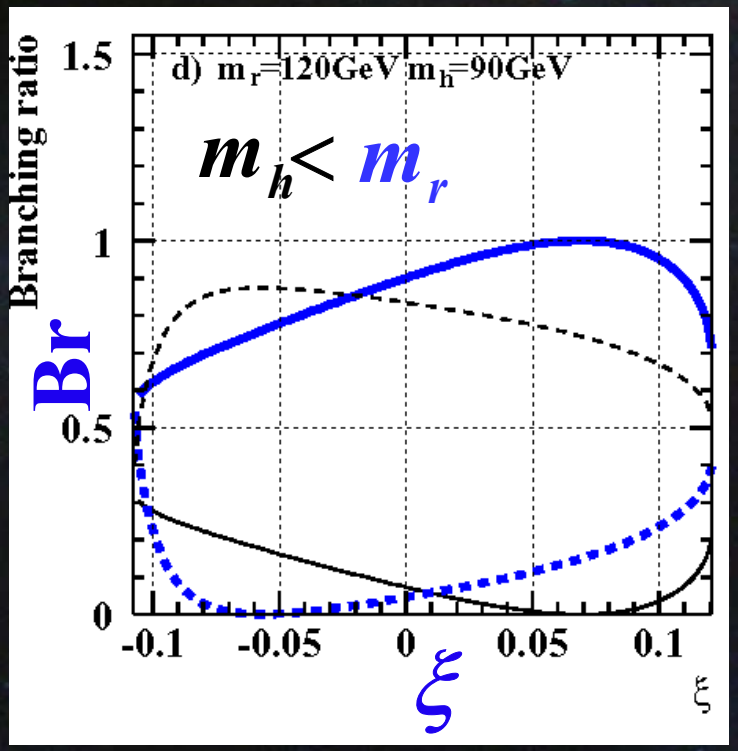
Radion can decay directly to gluons from trace anomaly coupling to the energy-momentum tensor

$\tilde{r}, \tilde{h}$ **are mixed states with mixing parameter** ξ

$\gamma = v/\sqrt{6}\Lambda_W$ – **coupling suppression factor**

Radion Searches

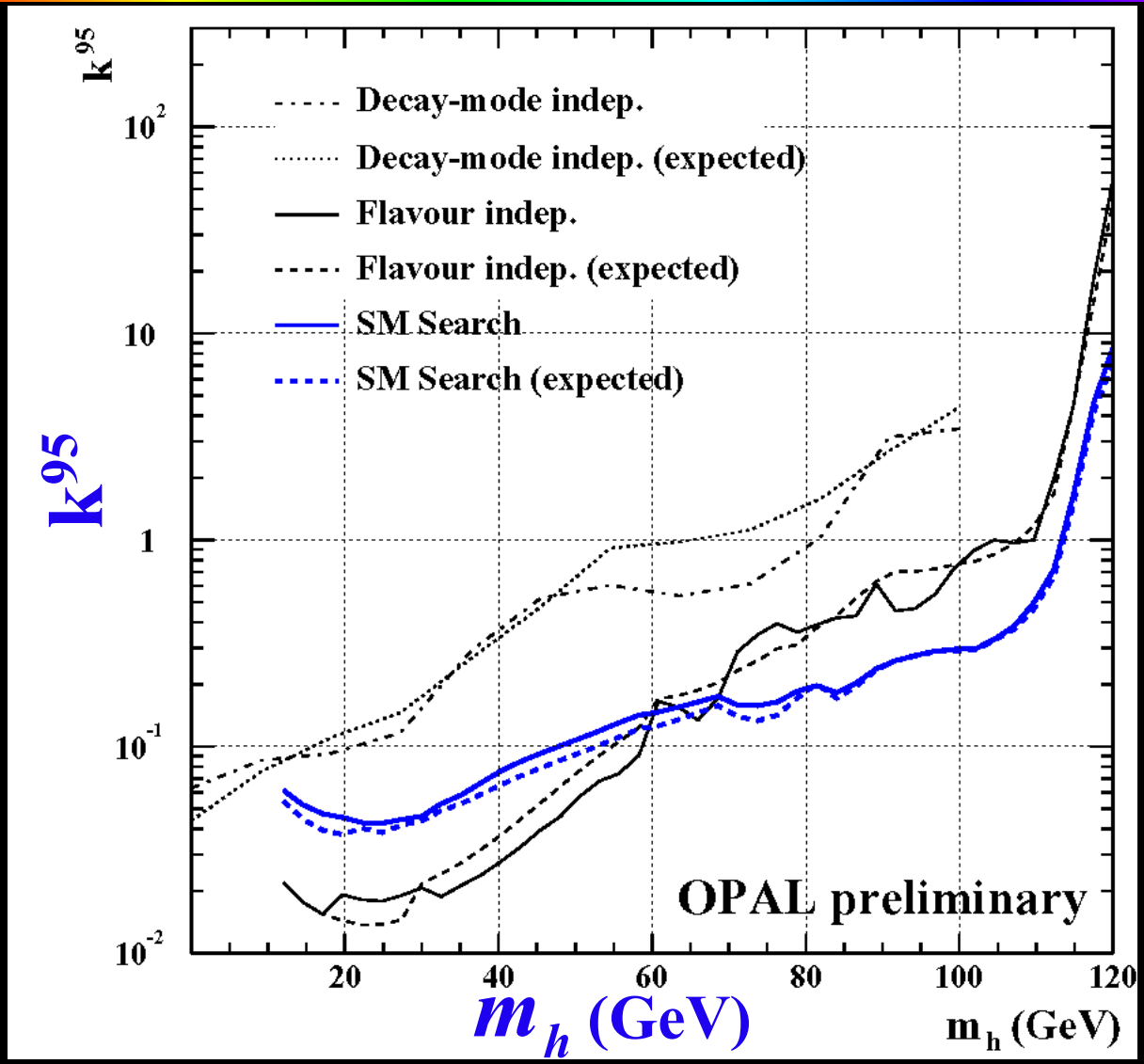




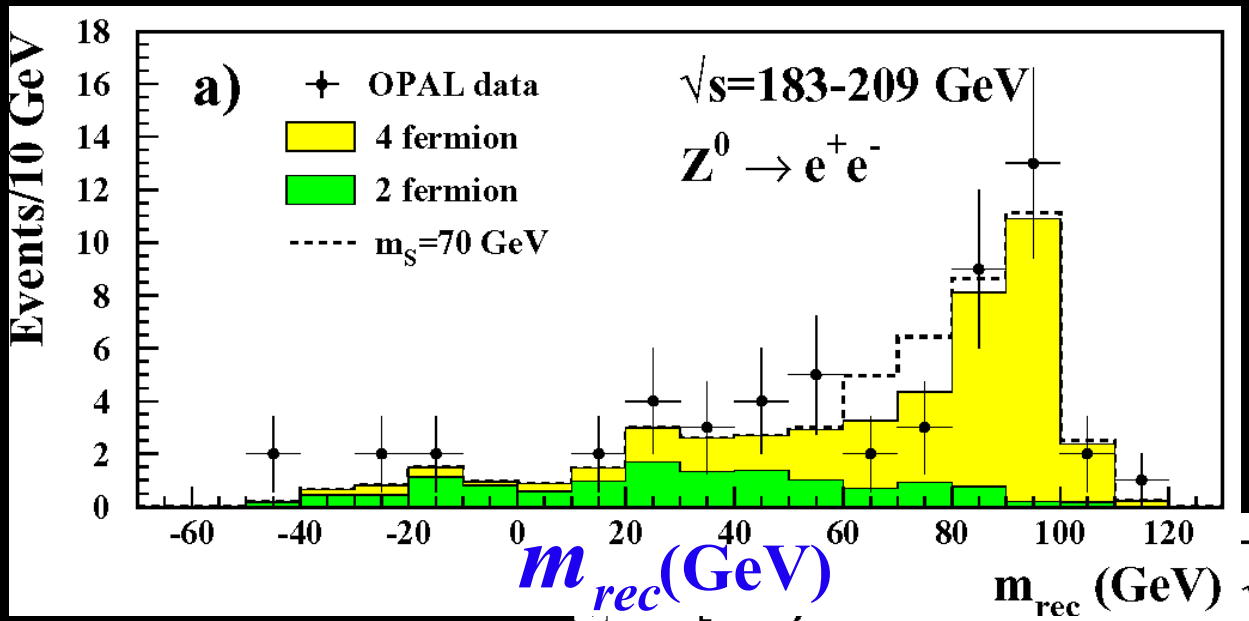
For several values of ξ, Higgs boson production is suppressed.

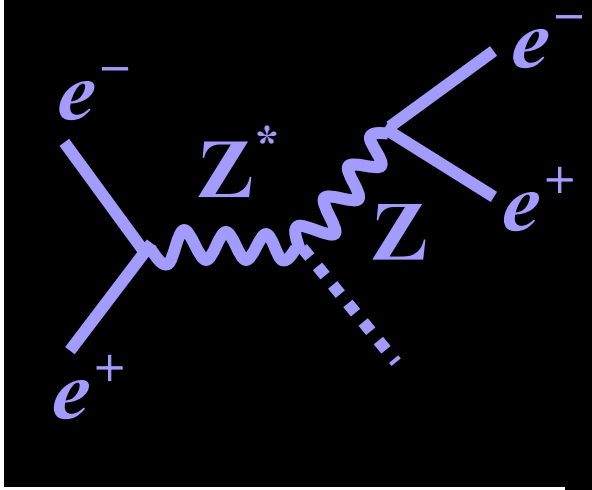
Role reversal in $Br\{\rightarrow \bar{b}b\}$ and $Br\{\rightarrow gg\}$

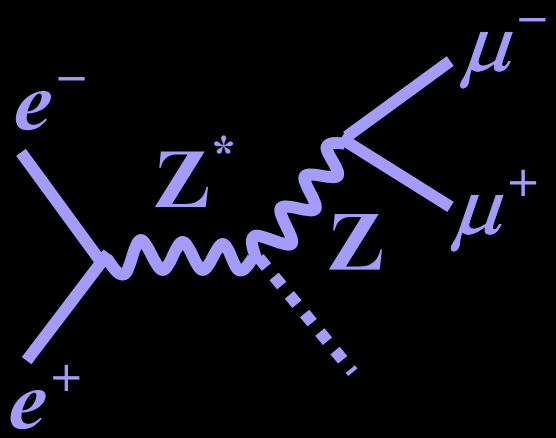
Radion Searches

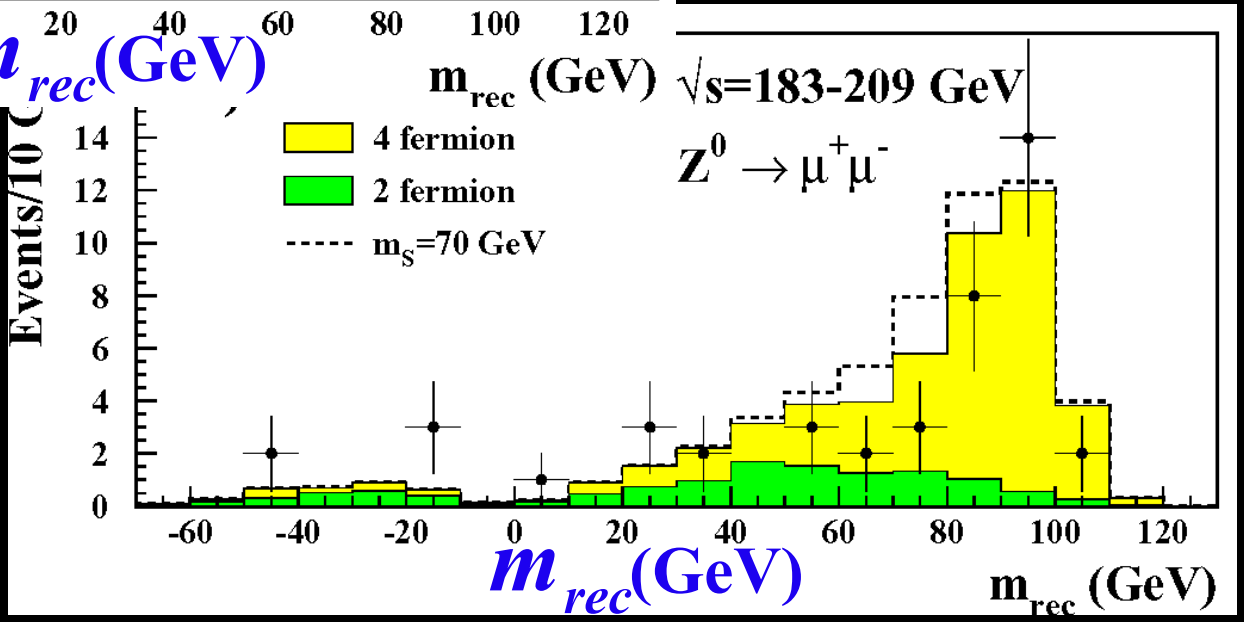


Decay Mode Independent

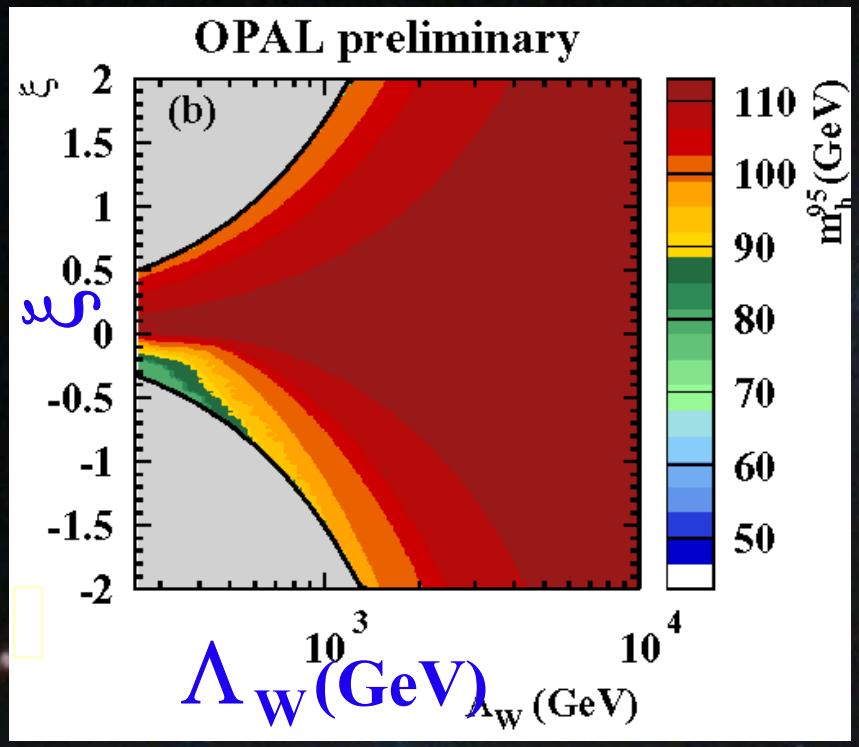


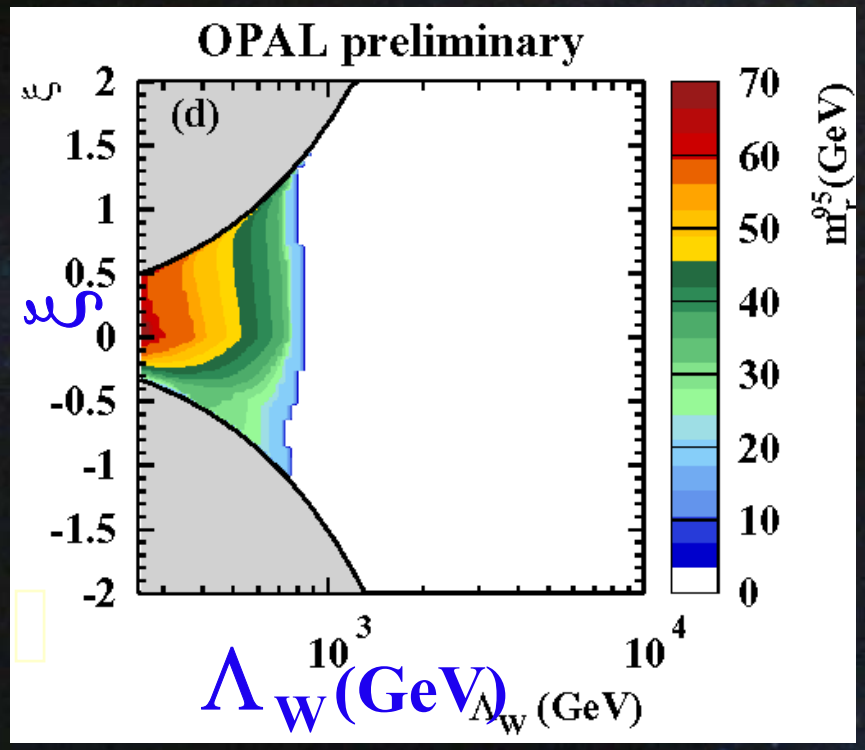






Radion Searches





Higgs Boson Exclusion

$m_h > 58\ \mathrm{GeV}/c^2$

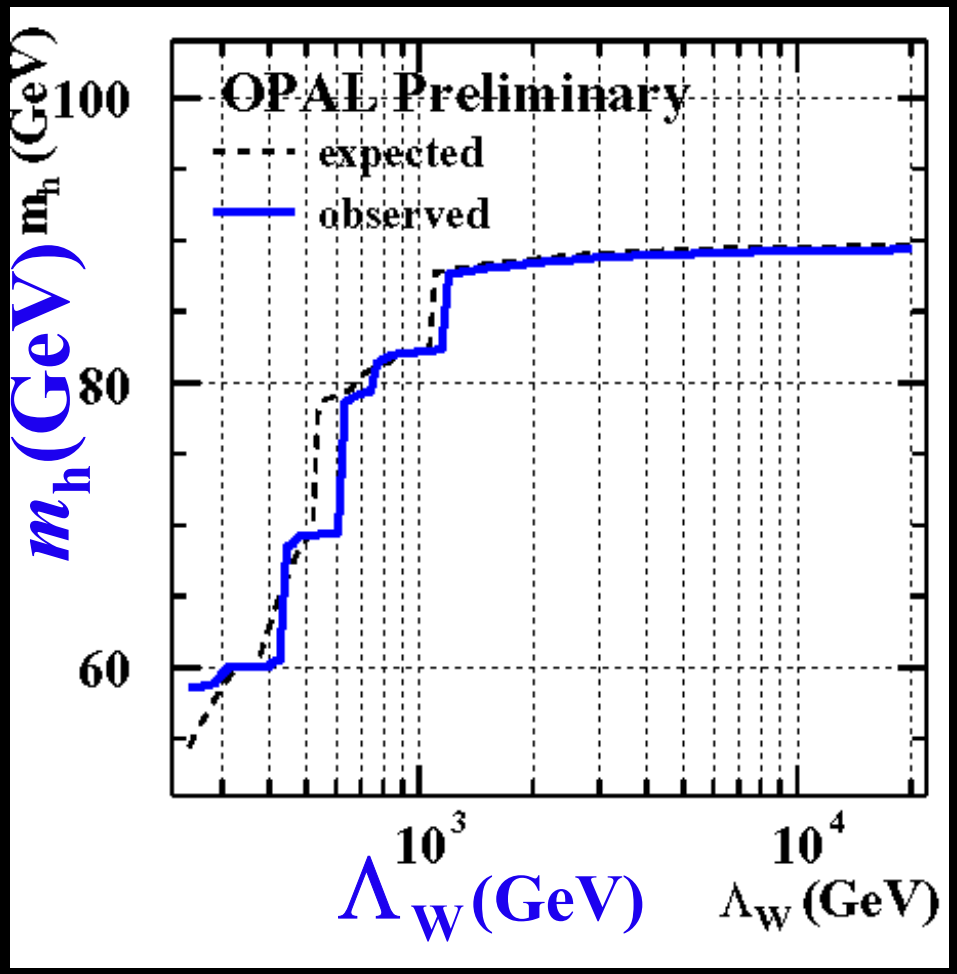
for $\Lambda_W > 246\ \mathrm{GeV}$

Radion Exclusion

Sensitive to

$\Lambda_W < 0.8\ \mathrm{TeV}$

Radion Searches



Searches for SUSY Particles

Gauge couplings carry over to super-partners:

Guarantees and Exceptions

Gauginos (fermions)

$$\left(W^{\pm}, H^{\pm}\right) \rightarrow \left(\chi_1^{\pm}, \chi_2^{\pm}\right)$$ **Charginos**

$$\left(B, W^0, H_u^0, H_d^0\right) \rightarrow \left(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0\right)$$ **Neutralinos**

↳ **Majorana fermions+mixing**

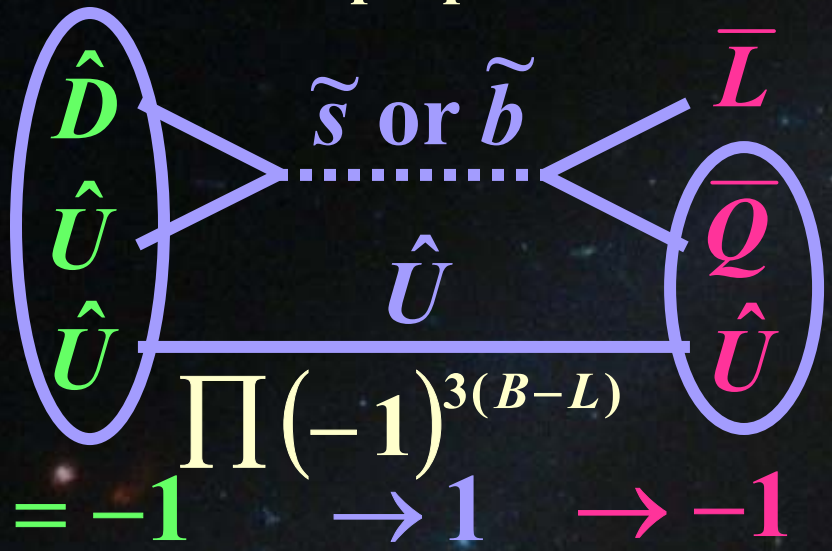
$$g(QCD) \rightarrow \tilde{g}$$

Supergravity is a broken gauge symmetry

$$G(Spin\ 2) \rightarrow \tilde{G}(Spin\ 3/2)$$ **Spin ±1/2 components from Super-Higgs Mechanism**

B-L Symmetry and R-Parity

Baryon and Lepton Violation from superpotential:



$$W_{\Delta B=1} = \lambda'_u \hat{U}\hat{D}\hat{D}$$

$$W_{\Delta L=1} = \lambda'_e \hat{E}\hat{L}\hat{L} + \lambda'_d \hat{D}\hat{Q}\hat{L} + \mu' \hat{L}\hat{H}_u$$

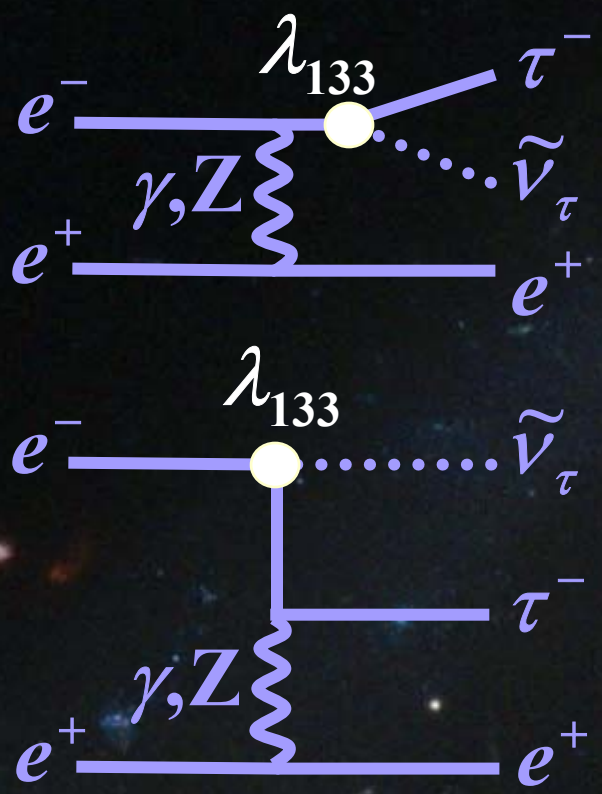
R-Parity Conservation

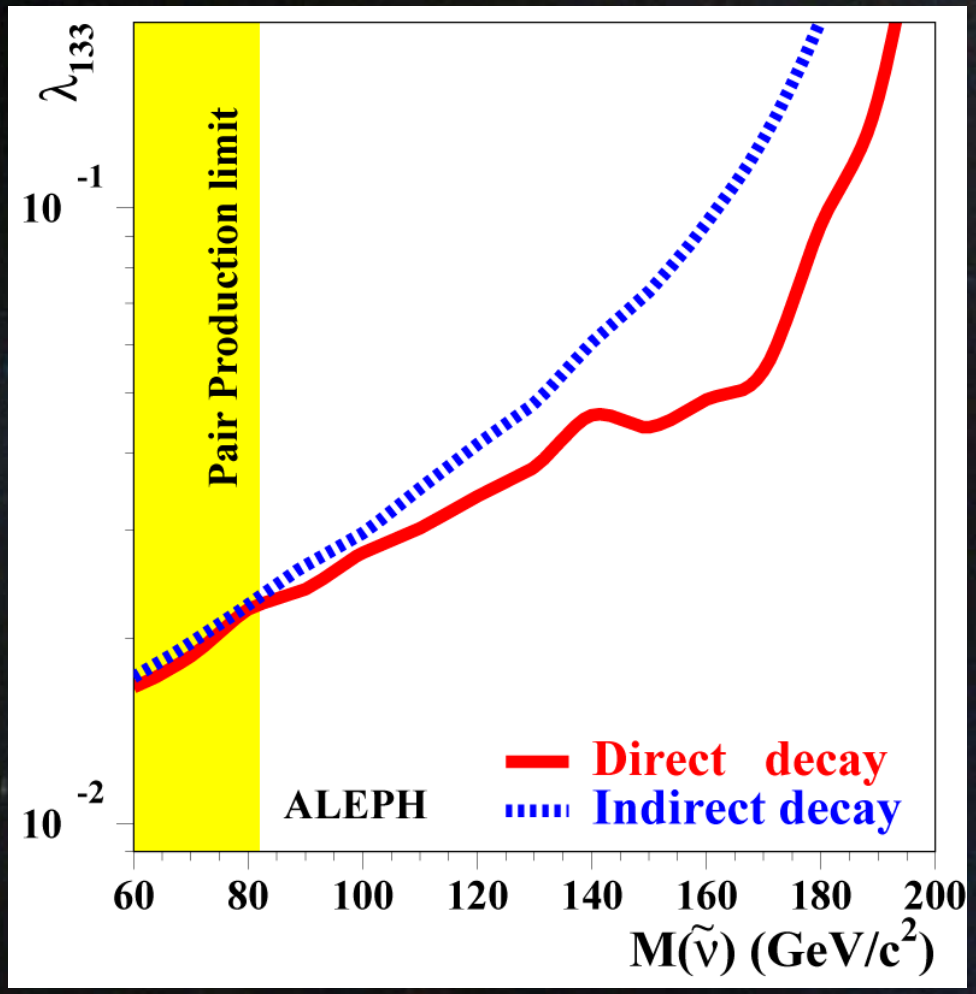
$$R_P = (-1)^{3(B-L)+2s}$$

- **Guarantees lightest sparticle(LSP) is stable**
- **Requires sparticles to be produced in pairs and decay in odd numbers**
- **Prevents proton decay (possible with *B-L* only)**

R-Parity Violating Searches

$$e^+e^- \rightarrow \tilde{\nu}_\tau \tau^- e^+$$





$LL\overline{E}$

Natural for Lepton Colliders

Resonant sneutrino production also possible.

Gravity-Mediated SUSY Breaking

Soft Breaking Scale from Gravity: $m_{soft} \propto \frac{\langle F \rangle}{M_{Pl}}$

Cascade Decays $e^+e^- \to \chi^0_{2,3}\chi^0_1$ **or** $\chi^\pm_1\chi^\mp_1$

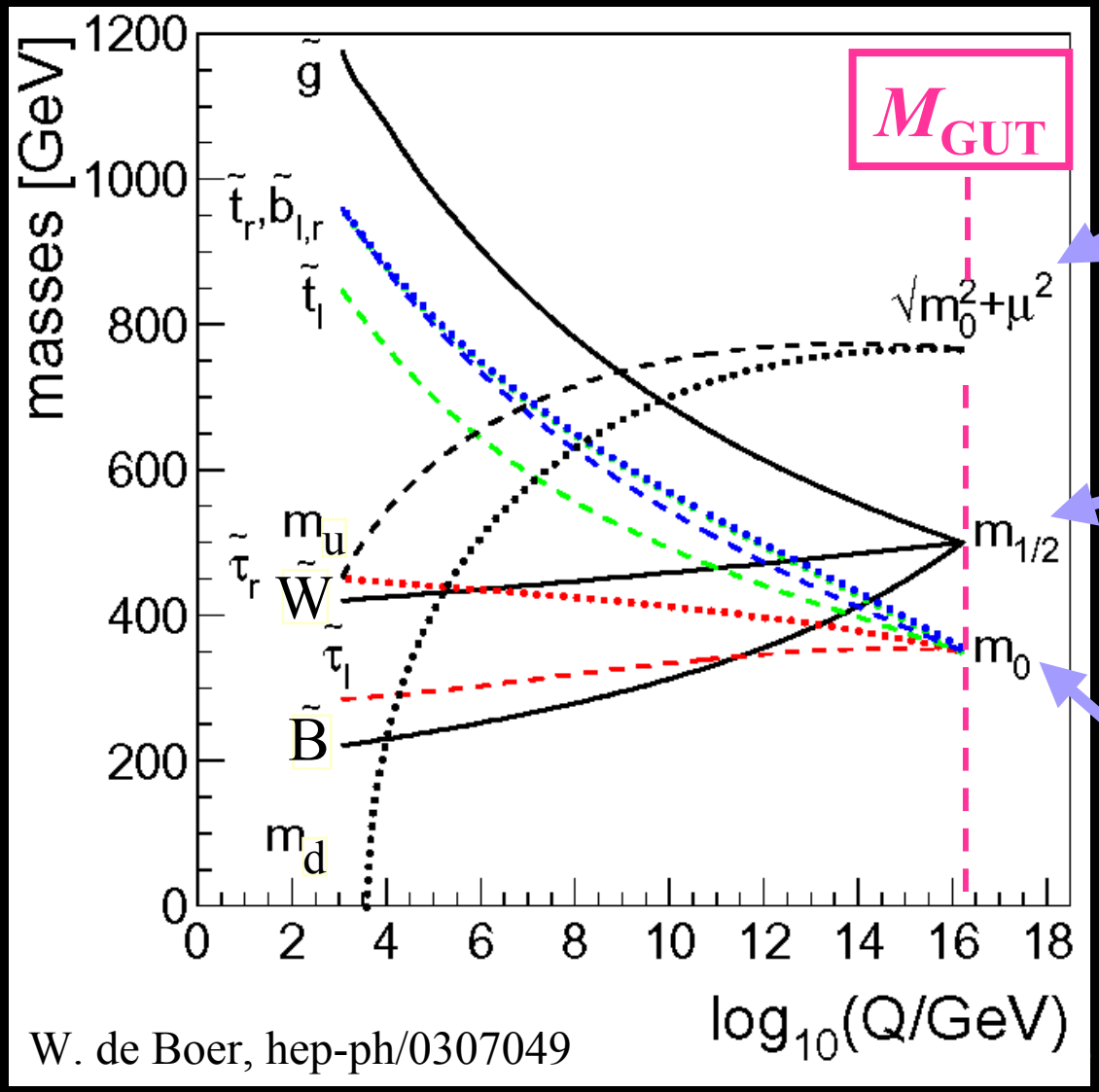
χ^0_1 **or** $\tilde{\nu}$ **as Lightest Supersymmetric Particle (LSP)**

$$\chi^0_2 \to \chi^0_1 + Z^*$$

$$\chi^\pm_1 \to \chi^0_1 + W^*$$

$$\chi^\pm_1 \to \tilde{\nu}\ell^\pm$$

mSUGRA Mass Evolution



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Higgs mass mixing strength

Unified **gaugino** masses

Unified **sfermion** masses

mSUGRA Mass Evolution

$SU(3)_C \times SU(2)_L \times U(1)_Y$

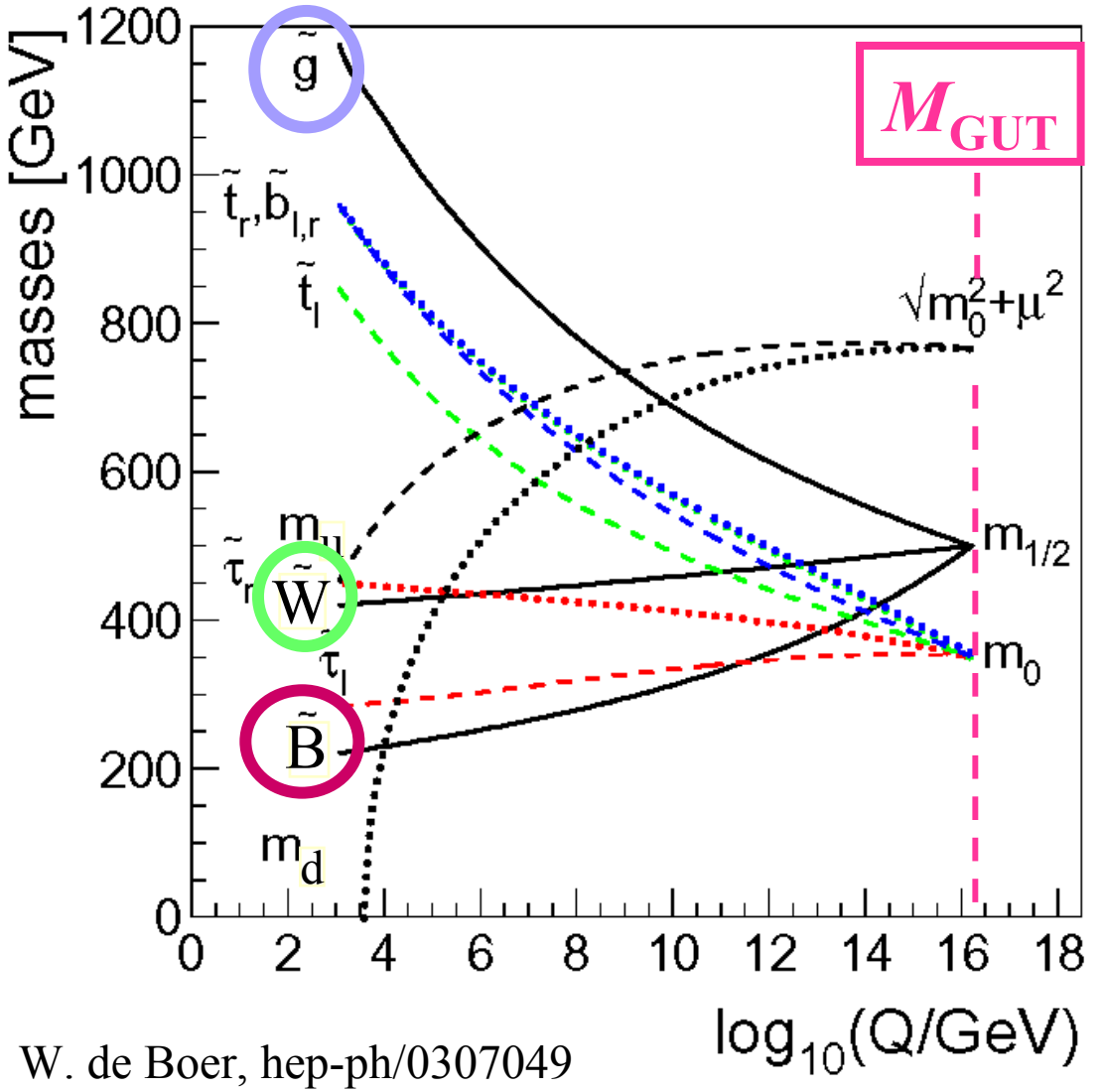
$$\frac{M_3}{g_3^2} = \frac{M_2}{g_2^2} = \frac{M_1}{g_1^2}$$

GUT implies heavy gluino $= \dfrac{m_{1/2}}{g_{GUT}^2}$

Mass mixing terms:

$$\propto m_t\left(A_t - \mu/\tan\beta\right)$$

$$\propto m_{b,\tau}\left(A_{b,\tau} - \mu\tan\beta\right)$$



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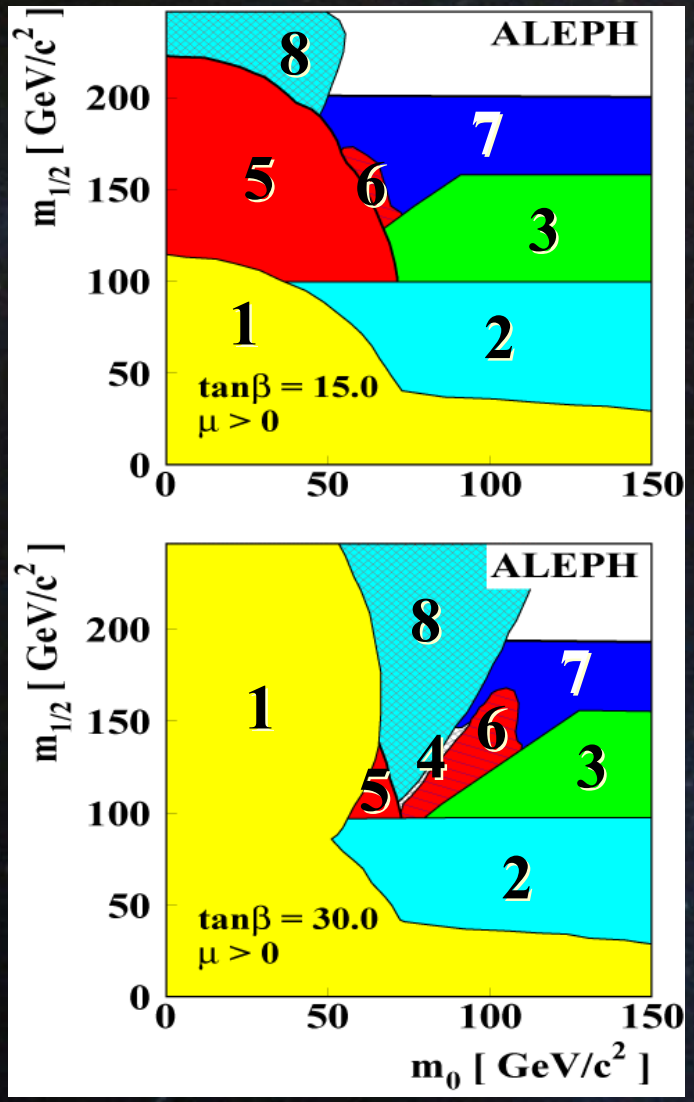
Gravity-Mediated SUSY Breaking

1) ***Theoretically forbidden***
2) **LEP1 Searches**
3) $\chi_1^{\pm}\chi_1^{\mp}$
4) $\chi_{2,3}^{0}\chi_1^{0}$
5) $\tilde{e}_R\tilde{e}_L$
6) $\tilde{\tau}_R\tilde{\tau}_L$ or $\tilde{\tau}_1\tilde{\tau}_2$
7) **Higgs boson searches**
8) **Stable charged particles**



Anomaly-Mediated SUSY Breaking

Nearly Degenerate Chargino and Neutralino

$$M_{\chi_1^0} \approx M_{\chi_1^\pm} \approx M_2$$

$$M_2 < M_1 < |\mu|$$

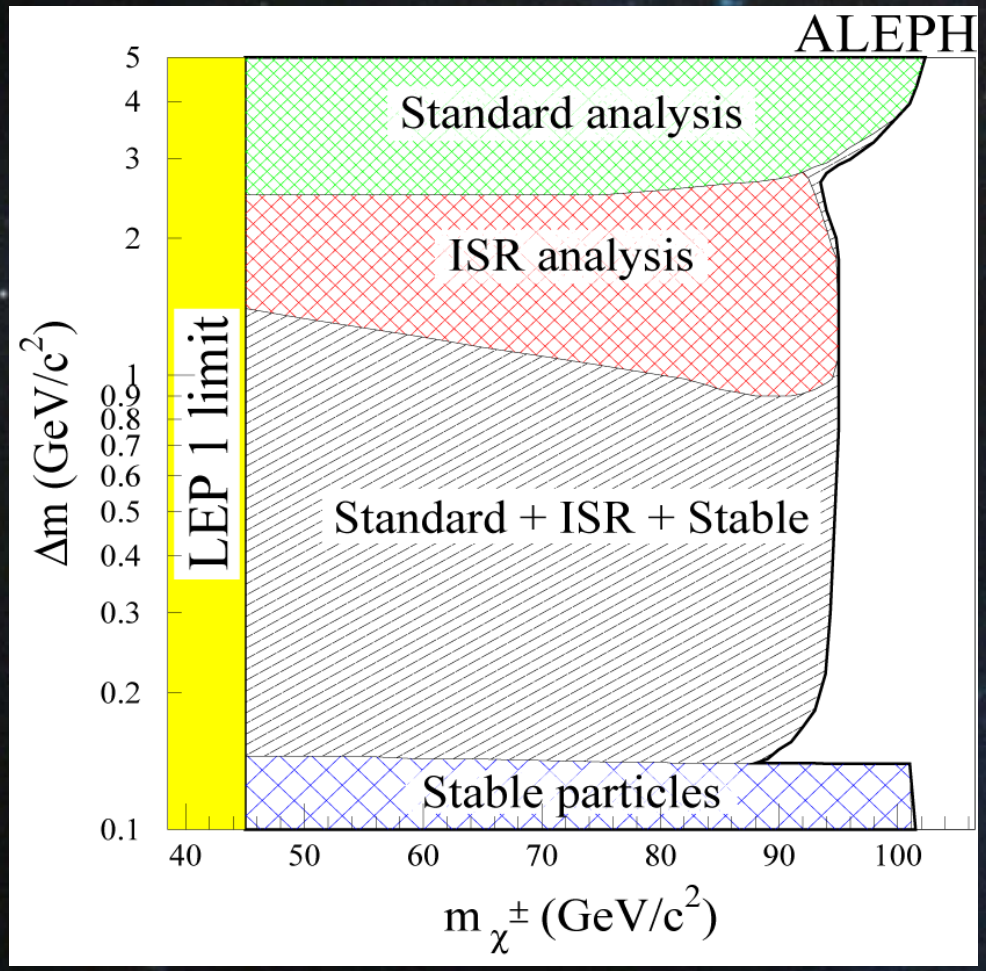
Wino - like LSP

$$\chi_1^0 \approx \tilde{W}^0$$

$$\chi_1^\pm \approx \tilde{W}^\pm$$

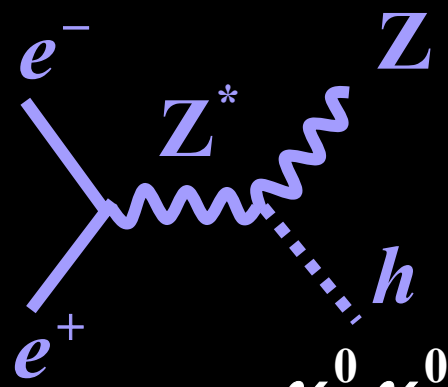
$$M_{\chi_1^\pm} > 88\ \mathrm{GeV}/c^2$$

$$m_{3/2} > 23\ \mathrm{TeV}/c^2$$



Invisible Higgs Search

Higgsstrahlung



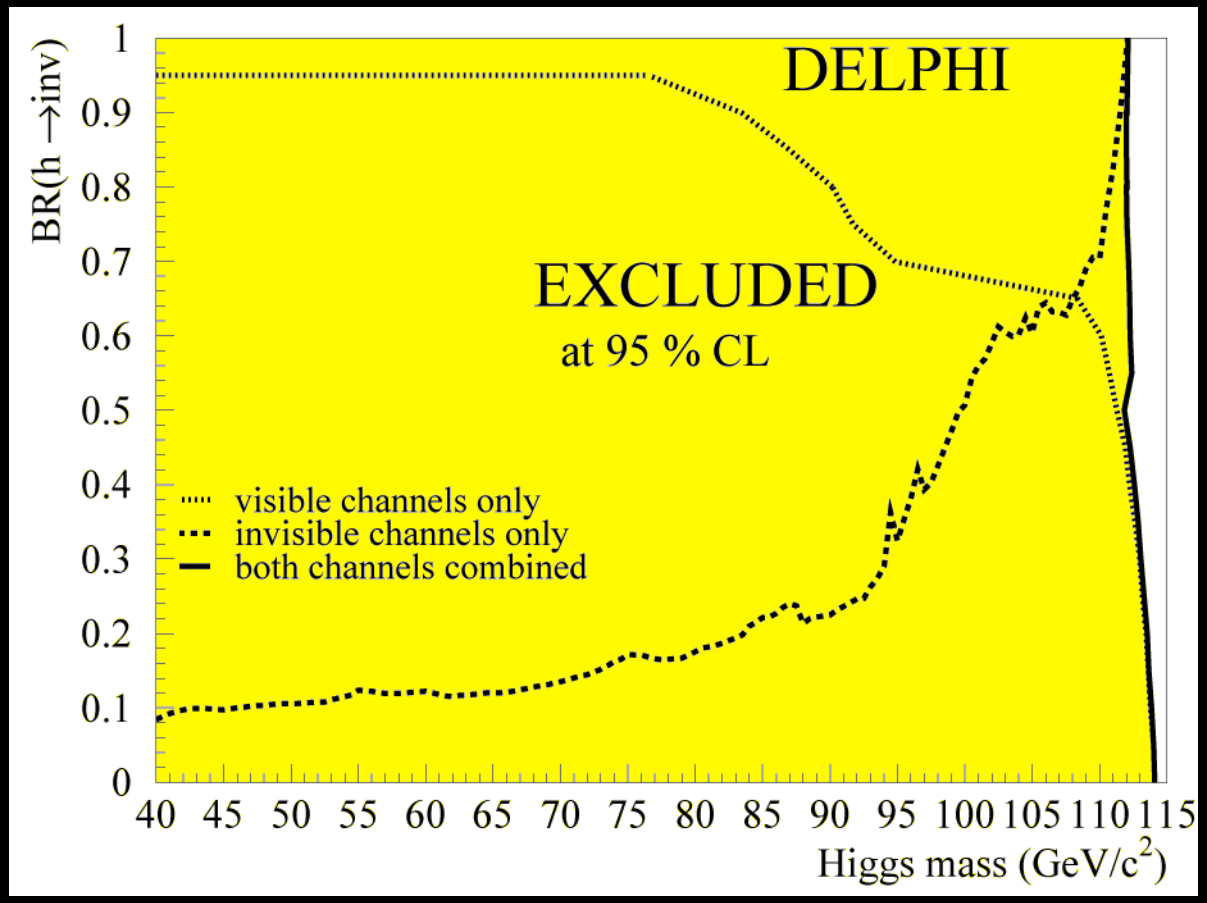
$\chi_1^0 \chi_1^0$

$\tilde{\nu}\tilde{\nu}$

$\tilde{l}\tilde{l}$ or $\chi_1^{\pm}\chi_1^{\mp}$

for $\Delta M \approx 0$

$m_h > 112.1\,\mathrm{GeV}/c^2$



Gauge-Mediated SUSY Breaking

Gravitino is LSP: $m_{3/2} << m_{soft}$

Super-Higgs mechanism gives

gauge-strength couplings to $\pm\frac{1}{2}$ terms

Next to Lightest Supersymmetric Particle (NLSP):

$$\tilde{\ell} \to \ell \tilde{G} \quad \text{and/or} \quad \chi_1^0 \to \gamma \tilde{G}$$

SUSY Particle Mass Scale Λ

$$M_i \approx N\Lambda \frac{g_i(M)}{4\pi}$$

Messenger Scale M

# of Messengers N

$$m_0^2(M) \approx 2N\Lambda^2 \sum k_i \left(\frac{g_i(M)}{4\pi} \right)^2$$

Gauge-Mediated SUSY Breaking

1) $\tilde{\ell}^+\tilde{\ell}^-$

2) $\chi_1^0\chi_1^0$

$\chi_1^0 \to \tilde{\ell}\ell$

$\tilde{\ell} \to \ell\tilde{G}$

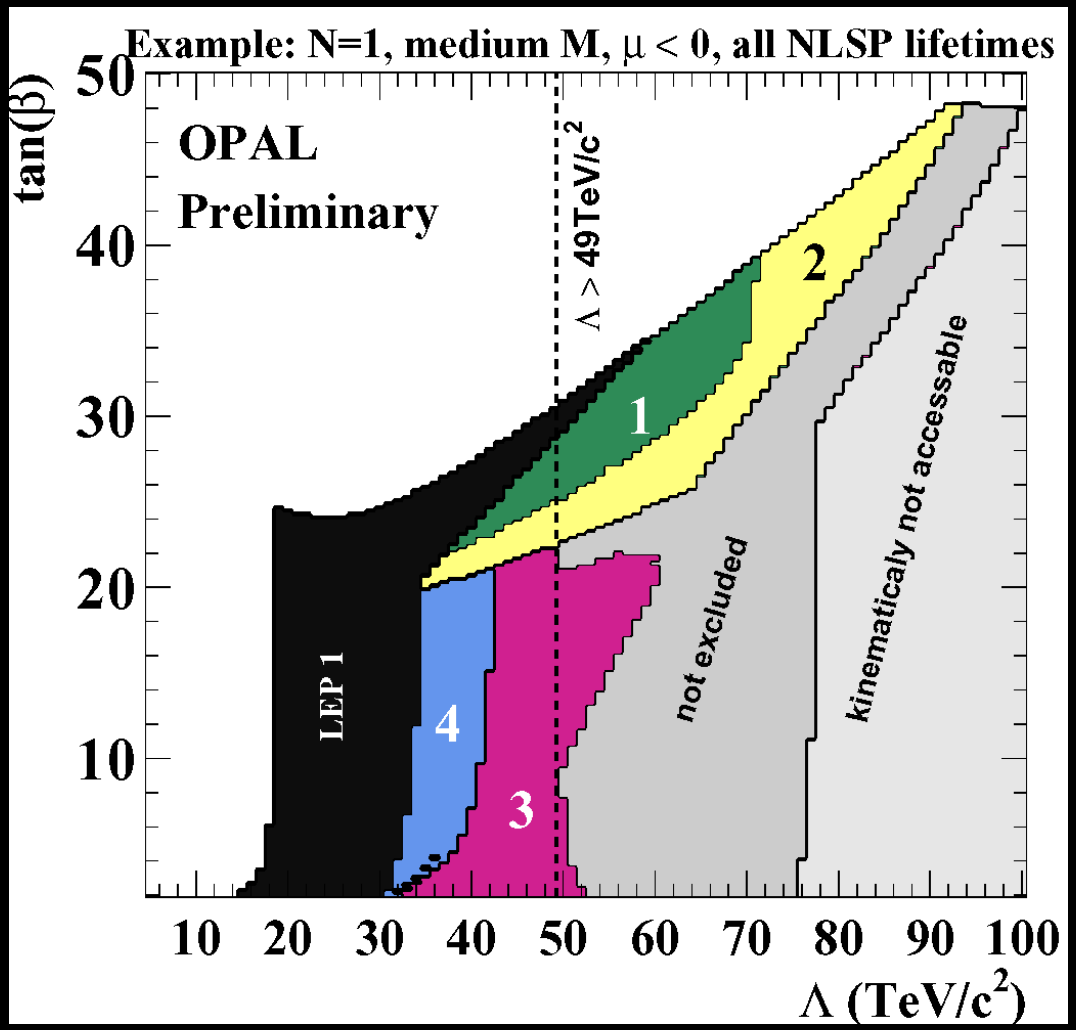
3) $\tilde{\ell}^+\tilde{\ell}^-$

4) $\chi_1^\pm\chi_1^\mp$

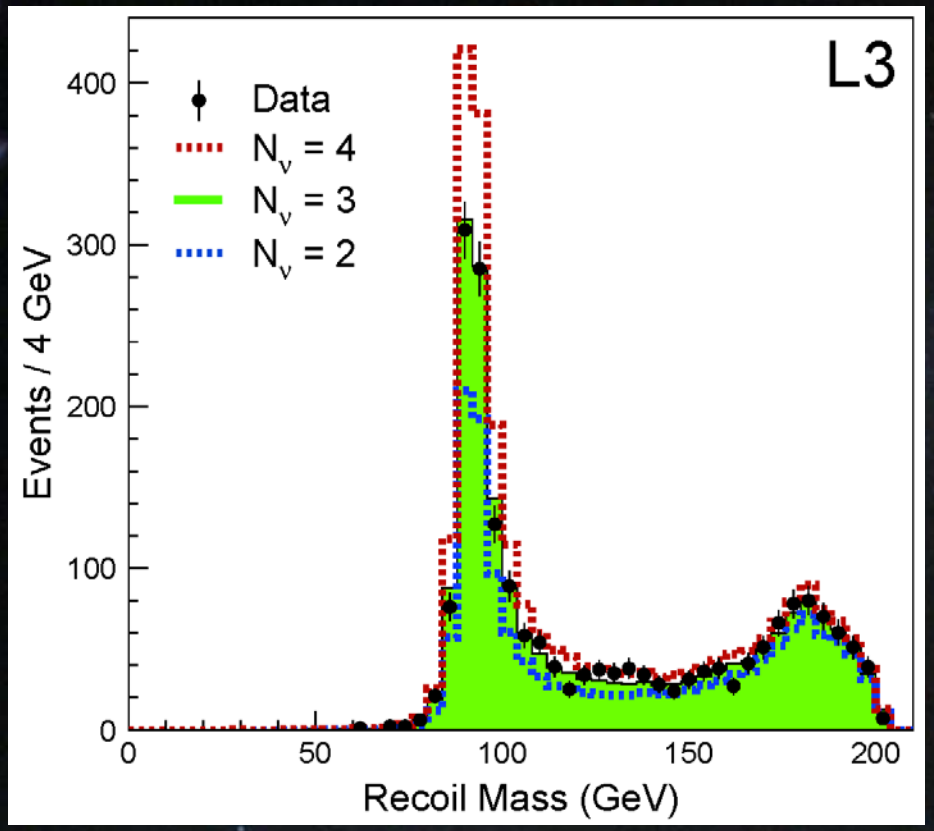
$\tilde{\ell} \to \chi_1^0\ell$

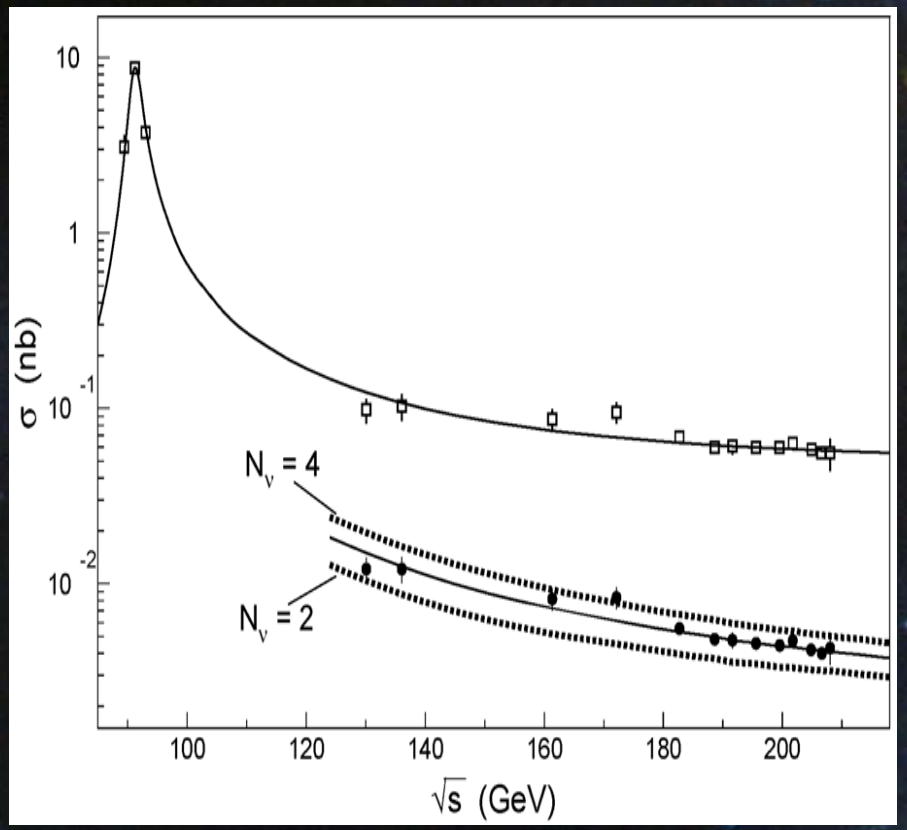
$\chi_1^\pm \to \chi_1^0 W^*$

$\chi_1^0 \to \gamma\tilde{G}$



Photons and Missing Energy





$$e^+e^- \to \tilde{G}\chi_1^0 \to \tilde{G}\tilde{G}\gamma$$

$$e^+e^- \to \chi_1^0\chi_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$$

$$N_\nu = 2.98\ (6)$$

MSSM Electroweak Fits

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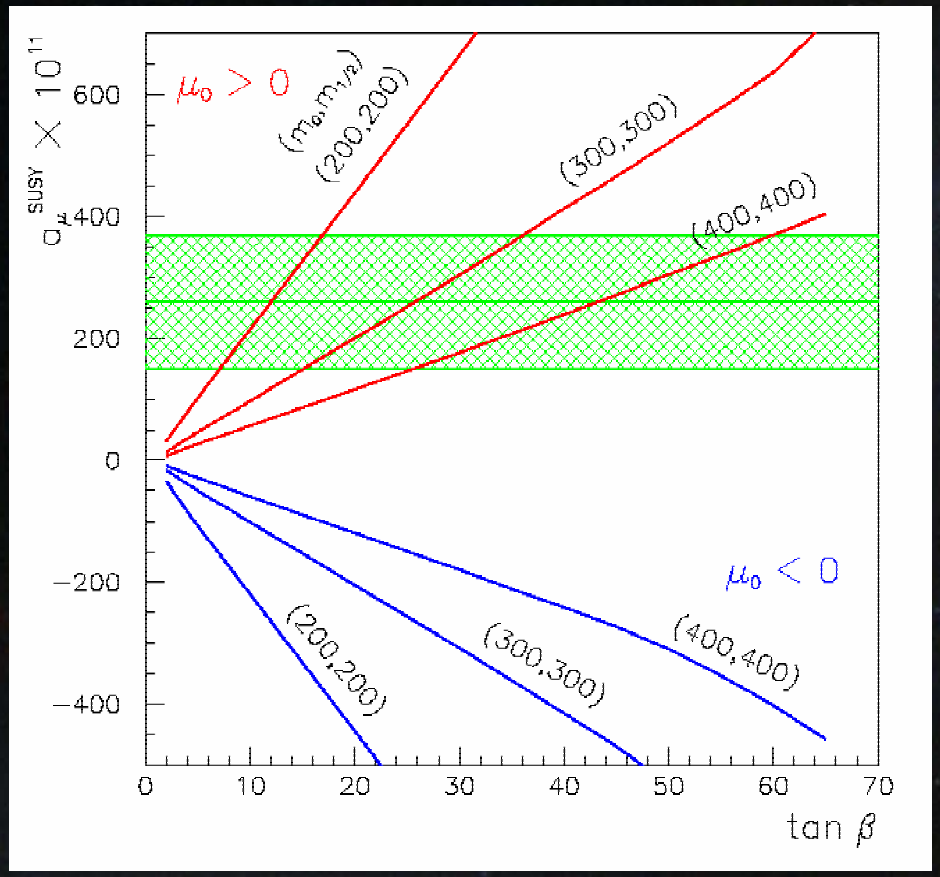

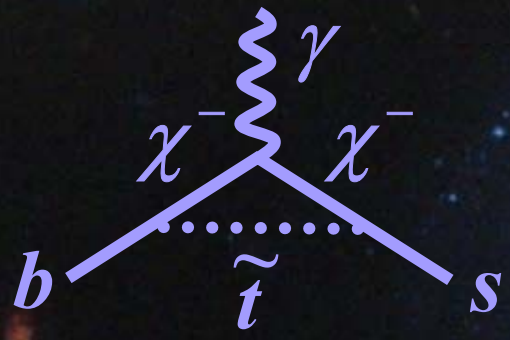

MSSM Electroweak Fits

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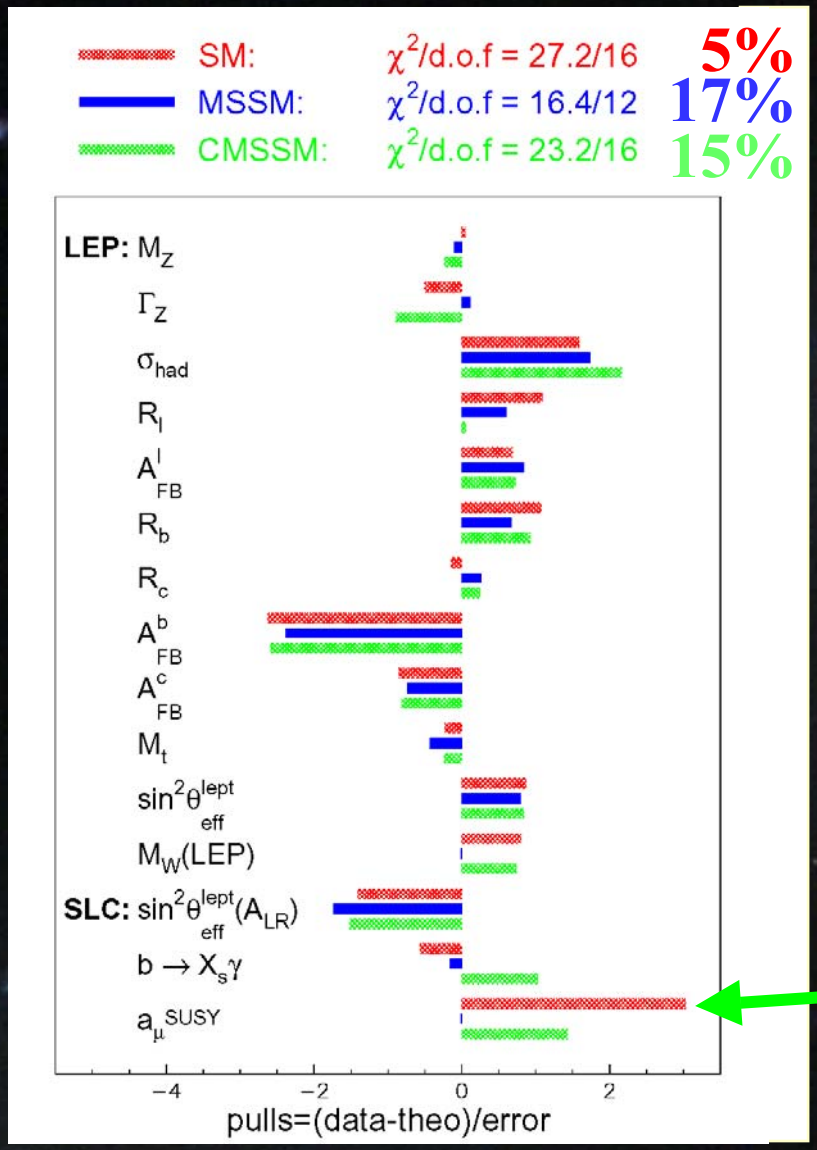
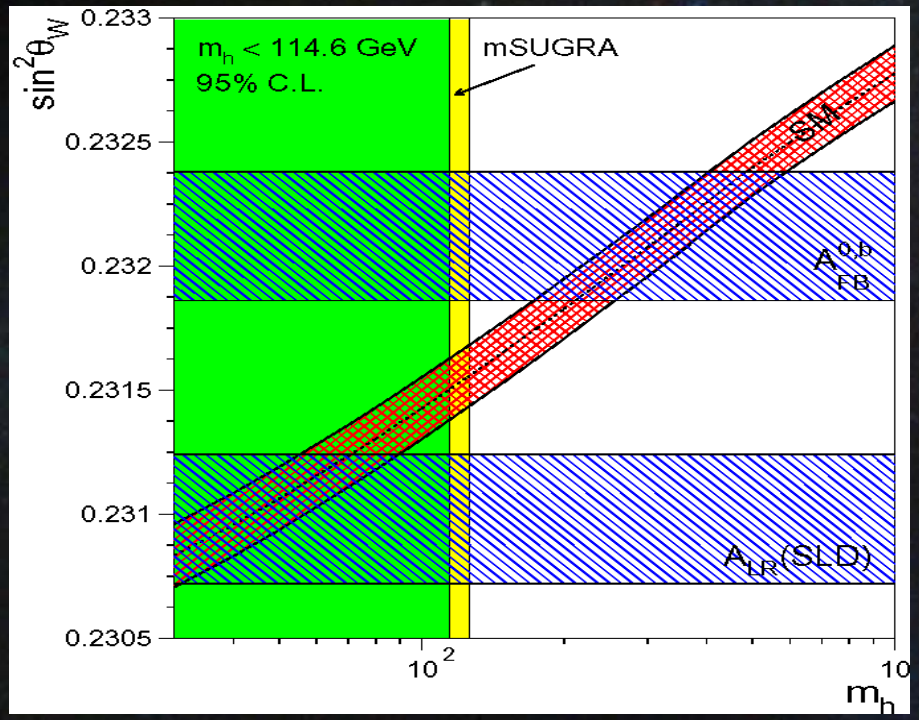
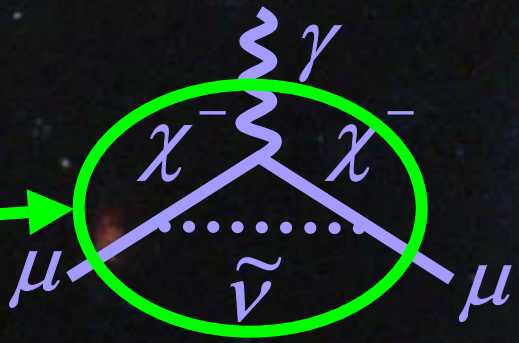
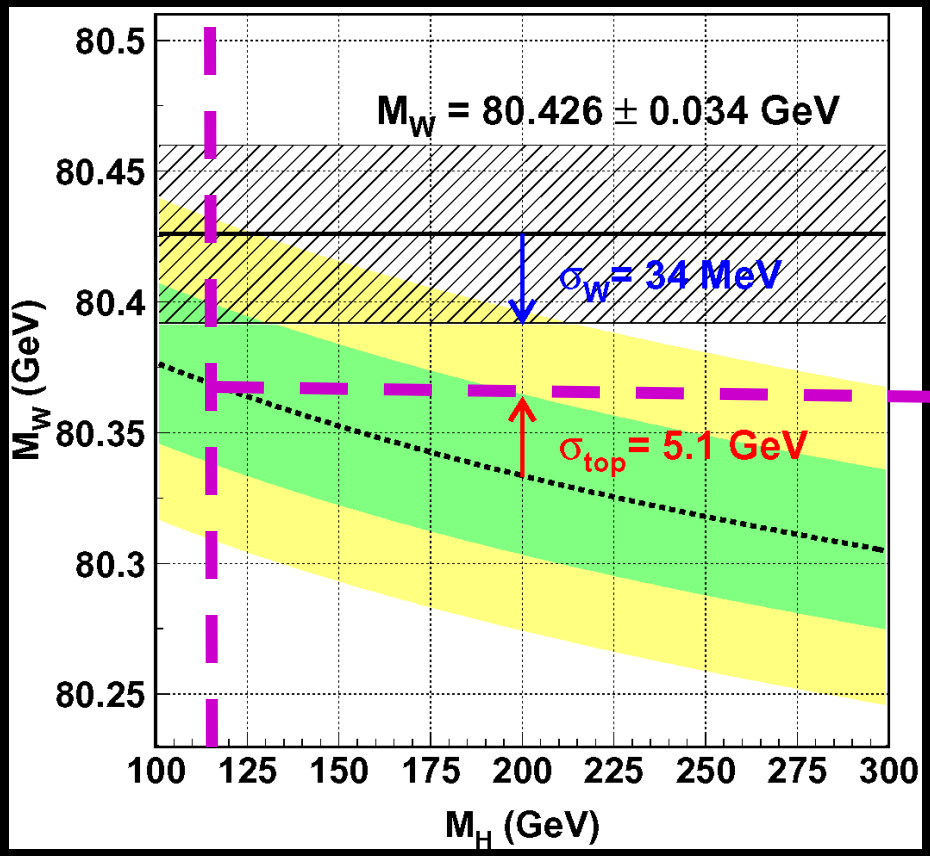
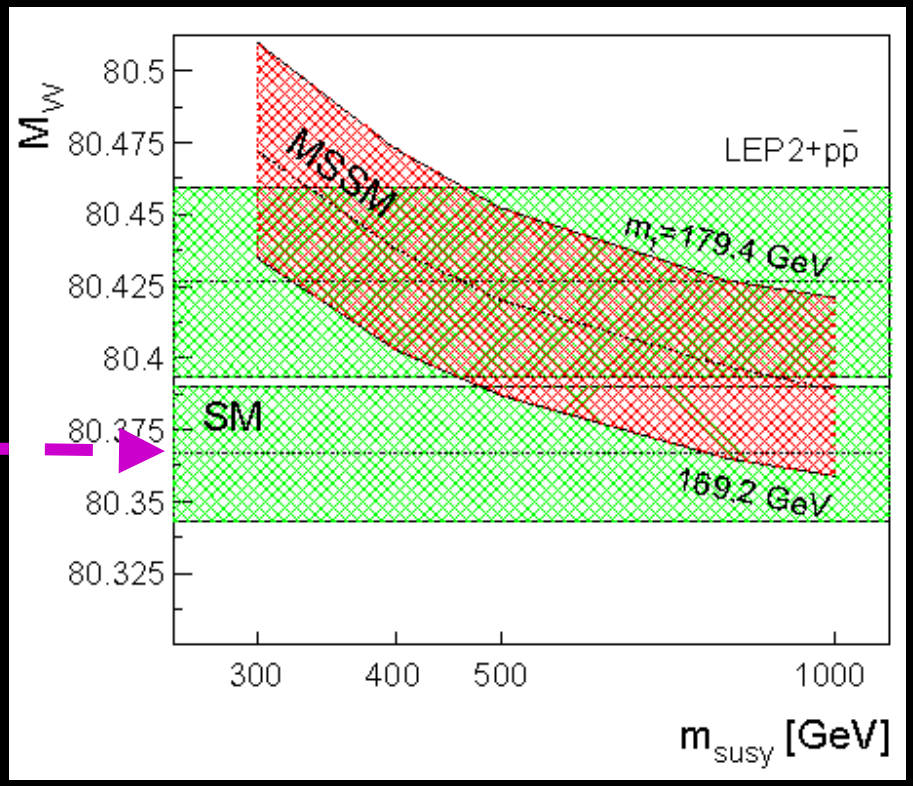
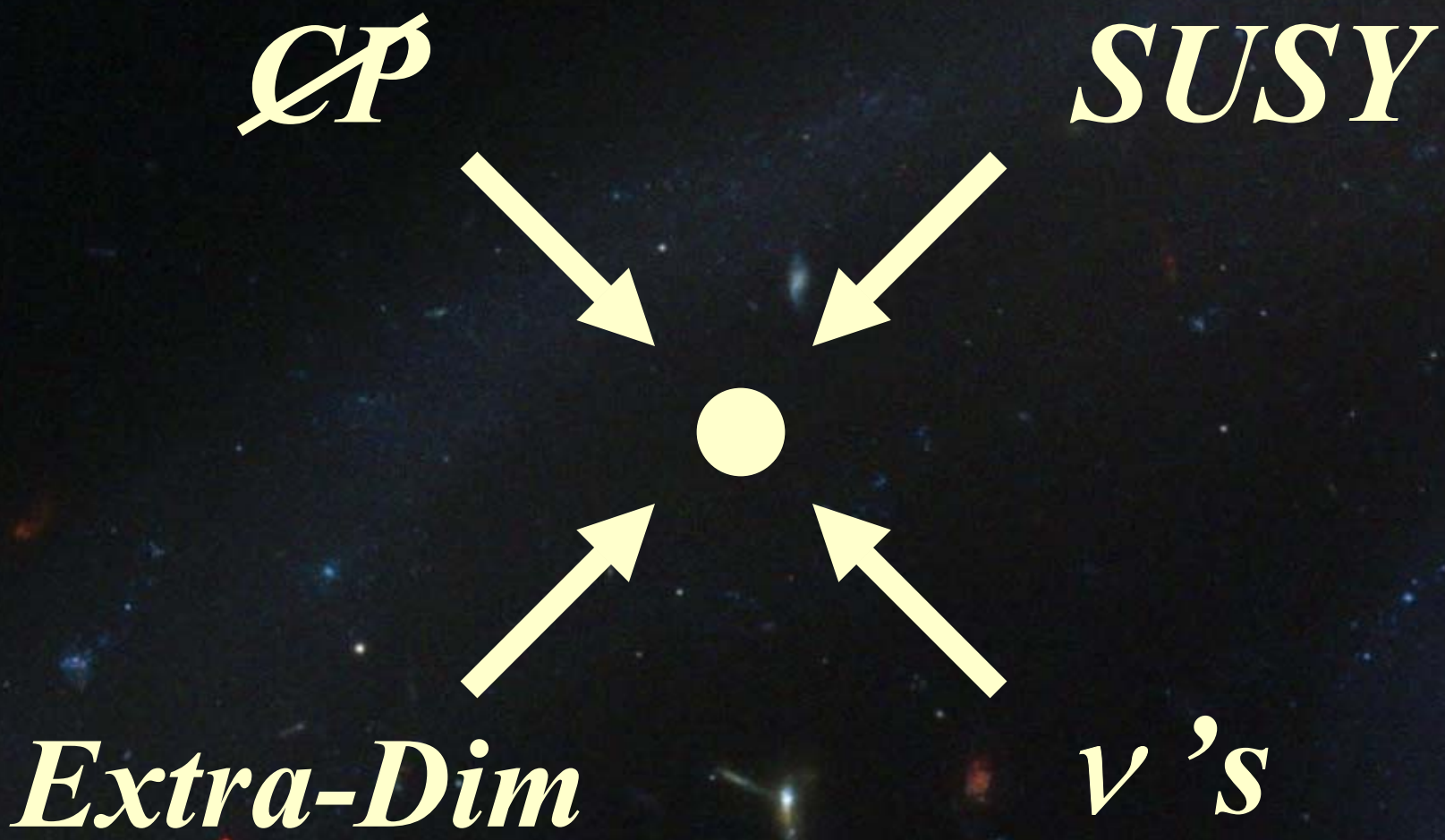






MSSM Electroweak Fits





Higgs Sector: Meeting Point