The scale-invariant NMSSM after the 125 GeV scalar discovery

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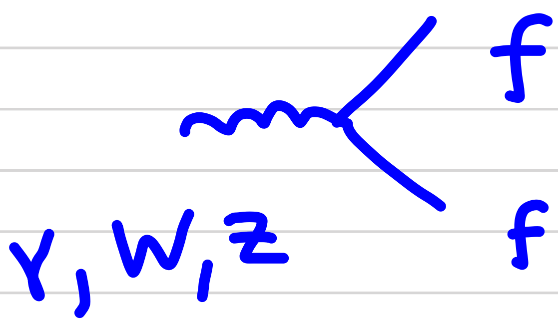
ArXiv:1209.2115
With K. Agashe and Y. Cui

OUTLINE

- INTRODUCTION
- HOW TO RAISE THE HIGGS MASS IN SUSY
- THE NMSSM
- NATURALNESS OF THE EW SCALE AND OF THE HIGGS MASS
- REGIONS OF INTEREST IN THE PARAMETERS SPACE
- CONCLUSIONS

STANDARD MODEL → $SU(2) \times U(1)$ GAUGE THEORY



AND

IN OVERALL GREAT AGREEMENT WITH DATA

⇨ DYNAMICS OF A GAUGE THEORY (LEP ERA)

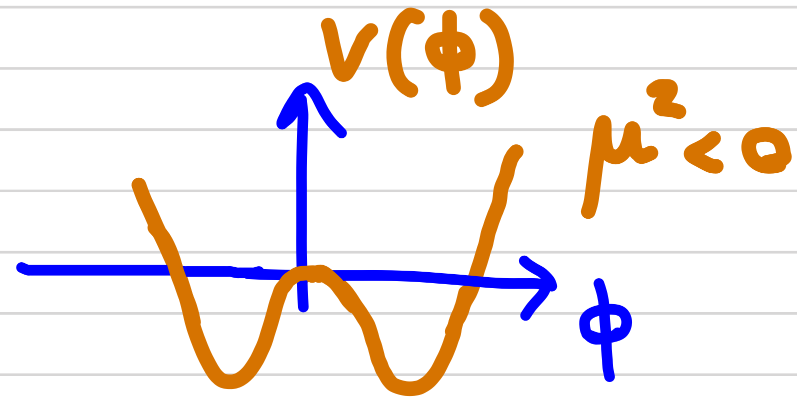
... UNLIKE QCD $m_{Z,W} \neq 0$

THE ELECTROWEAK SYMMETRY IS BROKEN

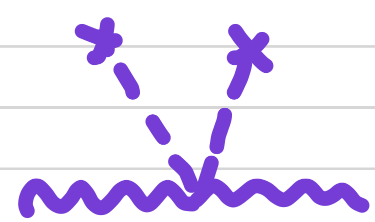
- SPONTANEOUS BREAKING
  - HIGGS MODEL $\mathcal{L} = |D_\mu \phi|^2$

    $\langle \phi \rangle = v$ BREAKS EW SYMMETRY

$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4$$

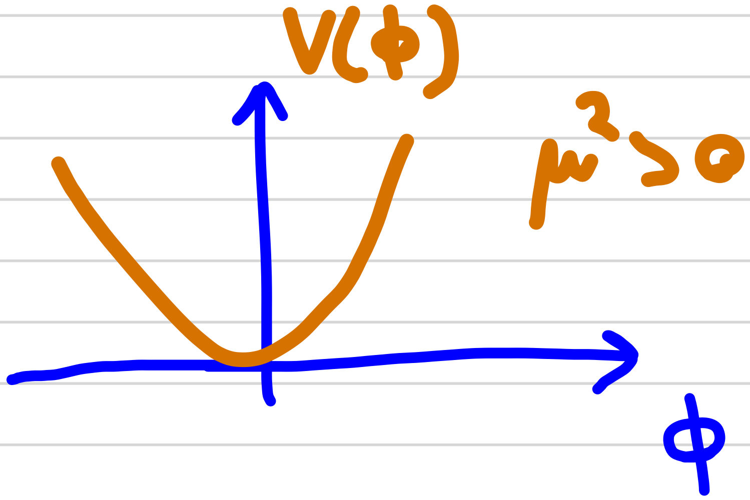


$$\langle \phi \rangle = v = \sqrt{-\frac{\mu^2}{2\lambda}} \gtrsim \frac{|\mu|}{4\pi}$$

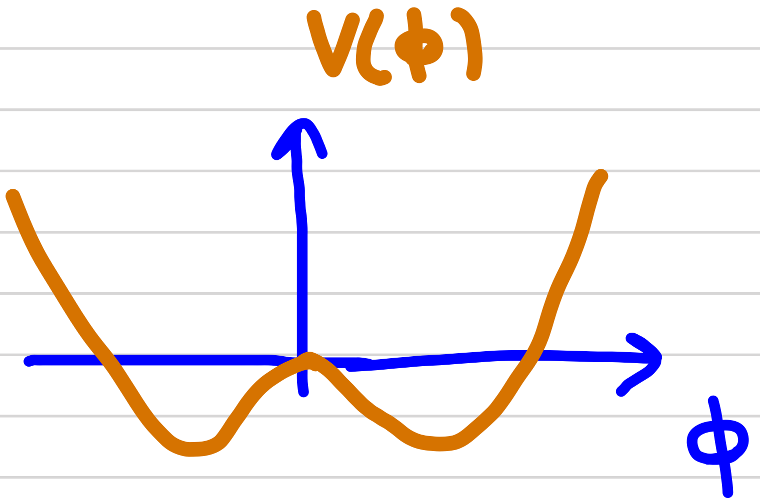


$m_W^2 \sim g^2 v^2$

THE POTENTIAL COULD HAVE BEEN DIFFERENT



$\langle \phi \rangle = 0$ UNBROKEN SYMMETRY



$\langle \phi \rangle \ggg m_W$

μ^2 is SENSITIVE TO UV CORRECTIONS

AND IN GENERAL $\mu^2 \sim \Lambda^2$ AT THE CUTOFF

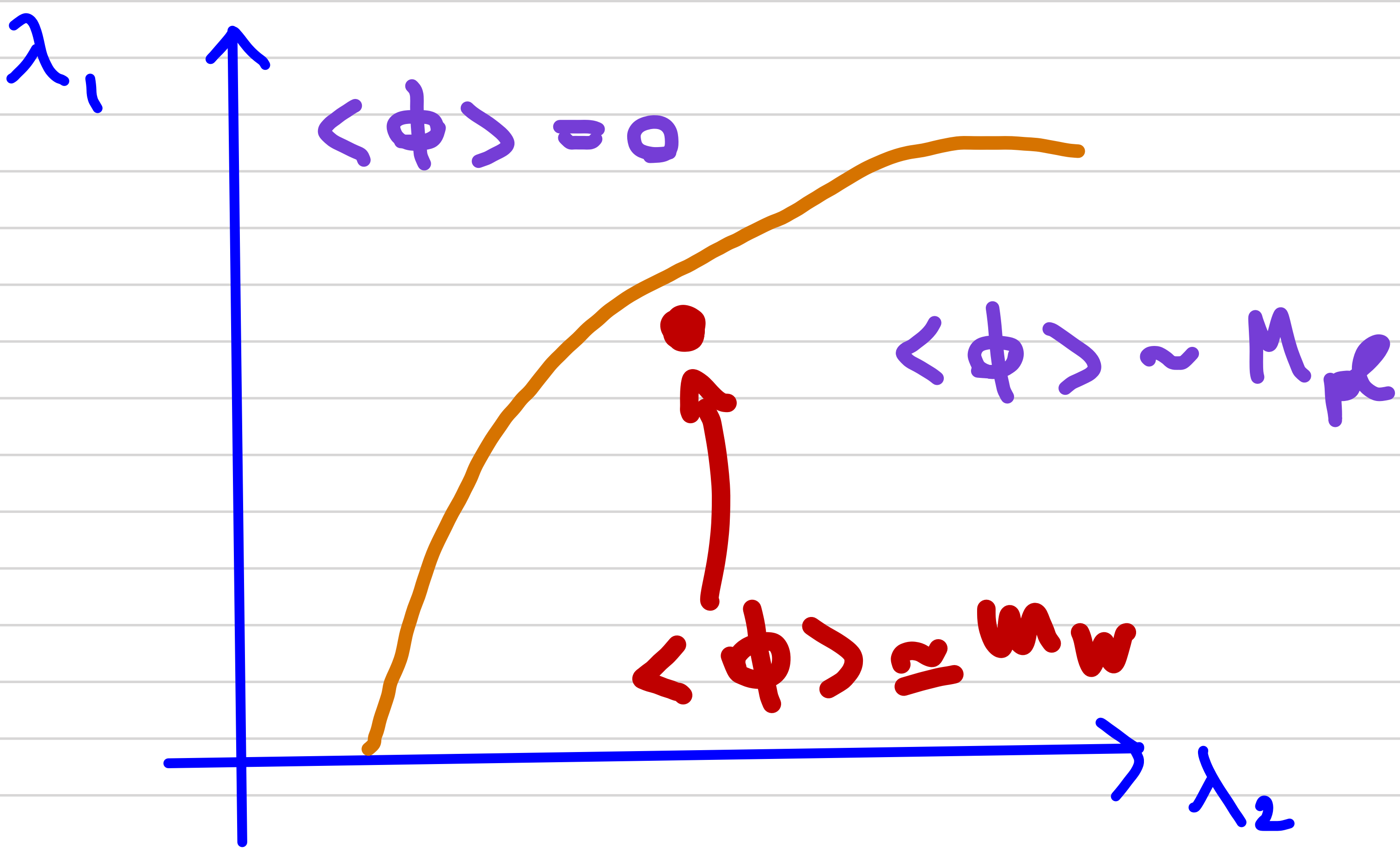
$\langle \phi \rangle$ is EXPECTED MUCH LARGER THAN m_W

PLANCK-WEAK HIERARCHY PROBLEM

$\langle \phi \rangle \sim \frac{m_W}{g}$ CAN BE ATTAINED IN THE STANDARD MODEL

BUT SEEMS UNNATURAL

OR AT LEAST POSES A QUESTION



- TeV MAY BE THE DYNAMICAL SCALE OF A STRONGLY INTERACTING THEORY

  $\mathrm{TeV} \sim \Lambda_{QCD}$

THE EW SCALE IS GENERATED BY DIMENSIONAL TRANSMUTATION

$\mathcal{L} + \lambda \delta \mathcal{L}_{breaking}$ $\lambda = \lambda_0$ at high-energy, $\dim \delta\mathcal{L} = 4 - \epsilon$

$\lambda(E) = \lambda_0 \left(\frac{\Lambda_{UV}}{E}\right)^{\epsilon}$ $\Lambda_{IR} \sim \Lambda_{UV} \lambda_0^{1/\epsilon}$ (hierarchy of scales)

- TeV is A MASS SCALE CONTROLLED BY A SYMMETRY

  m_f CHIRAL SYMMETRY $\Rightarrow$ SUSY

HIGGS MASS IN SUSY

SUSY RESTRICTS THE FORM OF THE HIGGS POTENTIAL

$V_h \supset$ "D-terms" FROM GAUGE INTERACTIONS

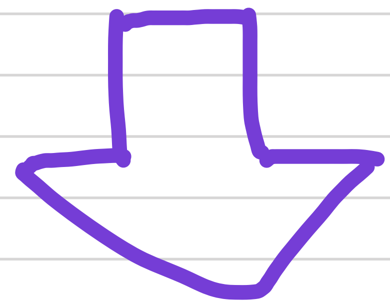
$$V_D \sim g^2 \left(|H_1|^2 - |H_2|^2 \right)^2$$

IN THE MSSM THERE IS NO OTHER SOURCE OF H^4

as a result $m_h \leq m_Z$ at tree-level

LEP-CRISIS

AFTER LEP $m_h \geq 114$ GeV



A LOT OF WORK TO "SAVE SUSY"

(next slides)

A LOT OF WORK ON NON-SUSY BSM

NEW CONTRIBUTIONS TO THE HIGGS MASS

- "F-terms" FROM NEW INTERACTIONS (non-gauge)

$$W \supset \lambda S H_1 \cdot H_2 \Rightarrow V_h \supset \lambda^2 |H_1 H_2|^2$$

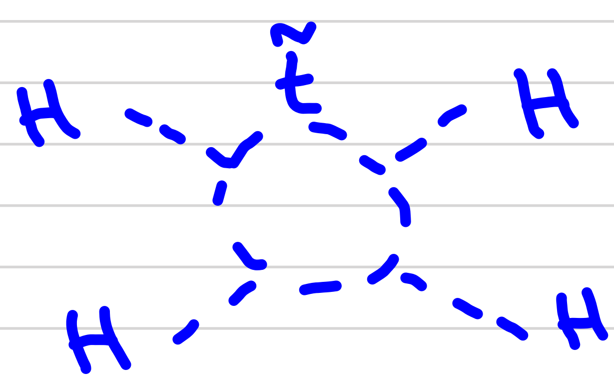
NEW INTERACTION (λ) — NEW FIELD (S)

$$\frac{d\lambda}{dt} \sim \lambda(\lambda^2 - g^2)$$

- new GAUGE INTERACTIONS $\Rightarrow$ "D-terms"

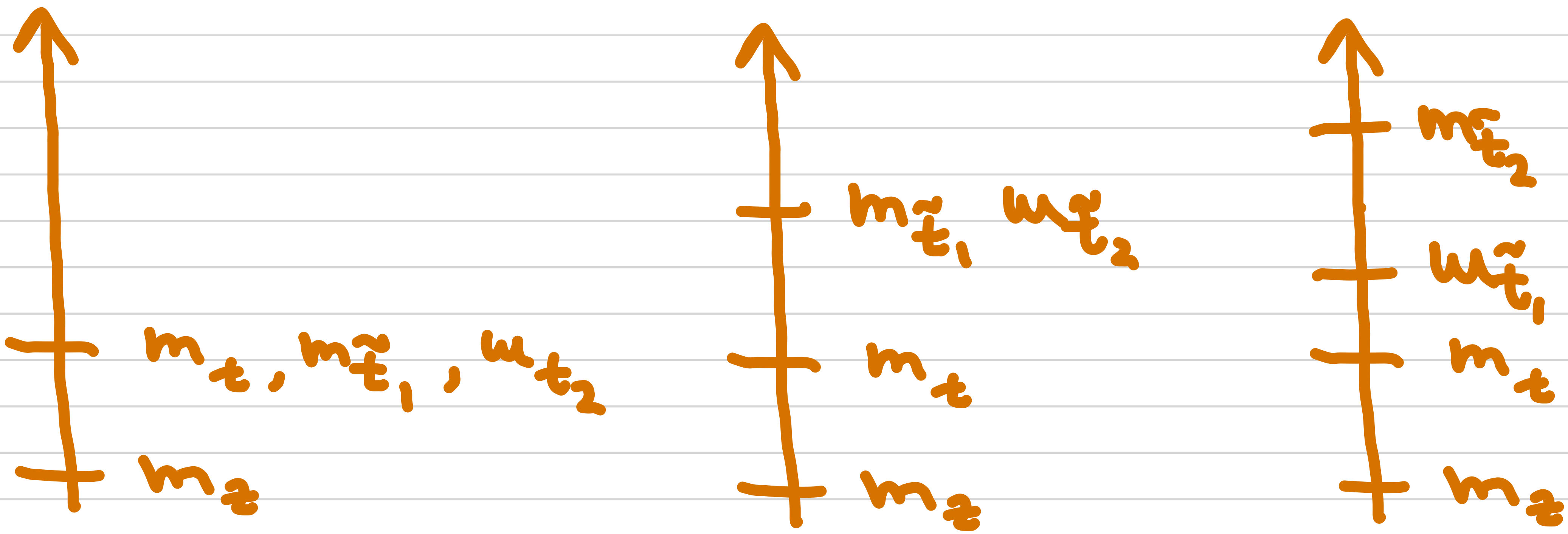
$$\delta V \supset g_x^2 \left(|H_1|^2 - |H_2|^2\right)^2 \frac{m_\phi}{m_\phi + m_{Z'}}$$

- LOOP CORRECTIONS



$$\sim \frac{y_t^4}{16\pi^2}$$

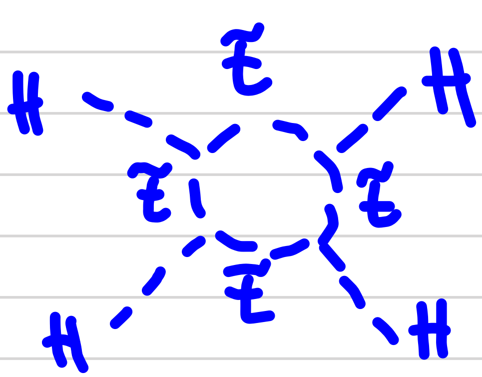
STRUCTURE of the LOOP CORRECTION



SUSY-limit

SMALL STOP MIXING

LARGE STOP MIXING



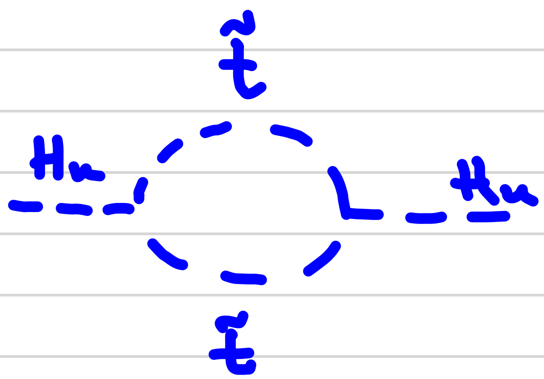
$$\delta(H_u^4) \sim \frac{3 y_t^4}{\pi^2}\left(\ln\frac{\overline{m}_{\tilde t}}{m_t} + X_t\right)$$

$$X_t \sim \frac{1}{\overline{m}_{\tilde t}^2}\left(A_t - \frac{\mu}{\tan\beta}\right)^2\left(6 - \frac{1}{\overline{m}_{\tilde t}^2}\left(A_t - \frac{\mu}{\tan\beta}\right)^2\right)$$

WITHOUT EXTRAS ON TOP OF THE MSSM ...

- LARGE STOP MASS AND MIXING ARE NEEDED

$$m_Z^2 = -|\mu|^2 - \frac{m_{H_u}^2 \cdot \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$



$$m_{H_u}^2 \propto m_{\tilde{t}}^2$$

CANCELLATIONS AMONG PARAMETERS ARE REQUIRED $\Rightarrow$ $m_Z \lll m_{SUSY}$

Next to minimal (NMSSM)

$$W = \lambda \hat{S} \hat{H}_1 \hat{H}_2 + \frac{k}{3} \hat{S}^3$$

$$\mathcal{L}_{soft} \sim m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \lambda A_\lambda S H_u H_d + \frac{k}{3} A_k S^3$$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{loop} + \lambda^2 v^2 \sin^2 2\beta + \delta m_{mix}$$

← MSSM

← NMSSM

TREE-LEVEL

MOTIVATIONS

$W \supset \lambda \hat{H}_1 \hat{H}_2 \hat{S}$

- ONCE $\langle H_1 \rangle = v_1$ $\quad \langle H_2 \rangle = v_2$ $\quad \langle S \rangle = s$

  GENERATES A μ TERM $\quad \mu H_1 H_2 \quad \mu = \lambda s$

- $\frac{k^3}{3} \hat{S}^3$ $\quad k$ IS THE ONLY OTHER INTERACTION WITH DIMENSIONLESS COUPLING (SCALE INVARIANCE? DISCRETE Z_3 ?)

OTHER VARIANTS ARE POSSIBLE

$W = m_s^2 \hat{S}^2 + \lambda \hat{S} \hat{H}_1 \hat{H}_2$ Hall, Pinner, Ruderman - arXiv:1112.2703

H_1 H_2 S

THEY CONTAIN CP-even SCALAR STATES

SO THERE ARE 3 MASS EIGENSTATES S_1 S_2 S_3

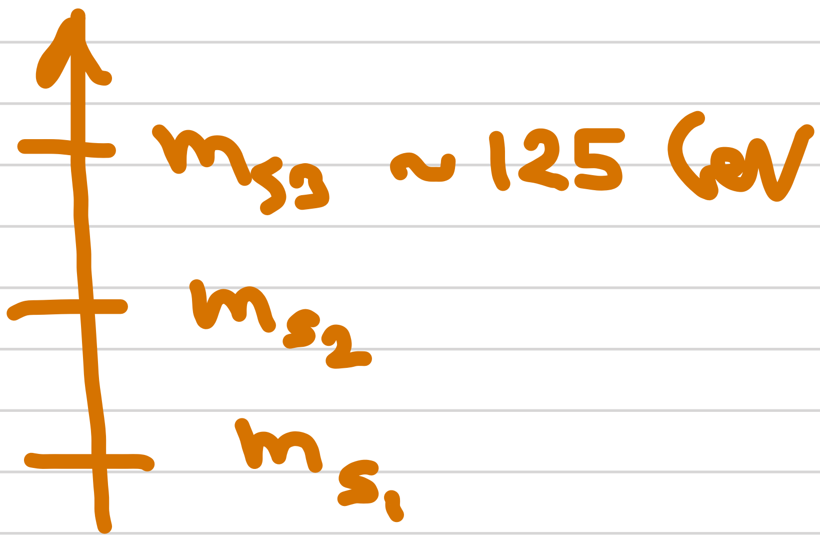
ONE COMBINATION IS GAUGE SINGLET

ONE COMBINATION COUPLES TO W^+W^-

THE ORTHOGONAL DOES NOT

THERE IS A CHARGED HIGGS AS IN THE MSSM

AND TWO PSEUDO-SCALARS



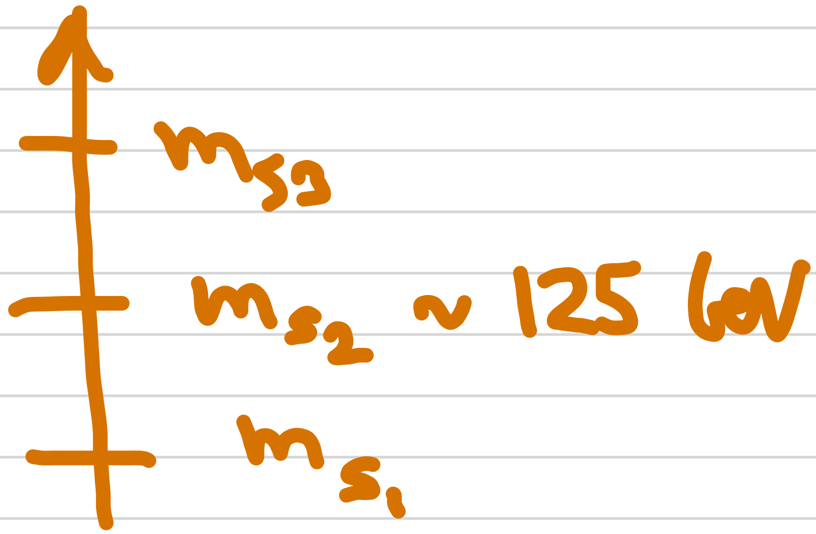
ALL THE HIGGS SECTOR IS LIGHT

ONE CHARGED LIGHT HIGGS

TWO PSEUDO-SCALARS

LEP, $b \to s \gamma$, ...

PUSH-UP SCENARIO



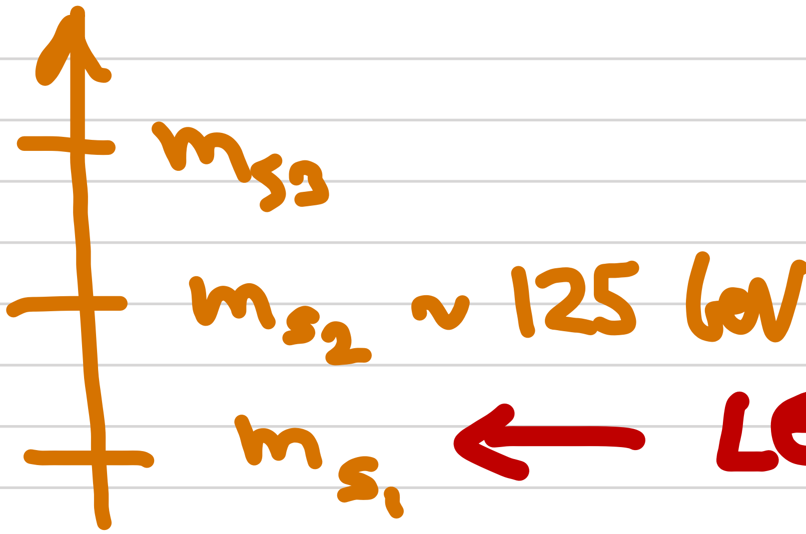
- ONE LIGHT SCALAR (in the reach of LEP?)
- CHARGED HIGGS MAY BE HEAVY
- ONLY ONE PSEUDO-SCALAR COULD BE LIGHT

$$h_i = \sum_j c_{ij} s_j$$

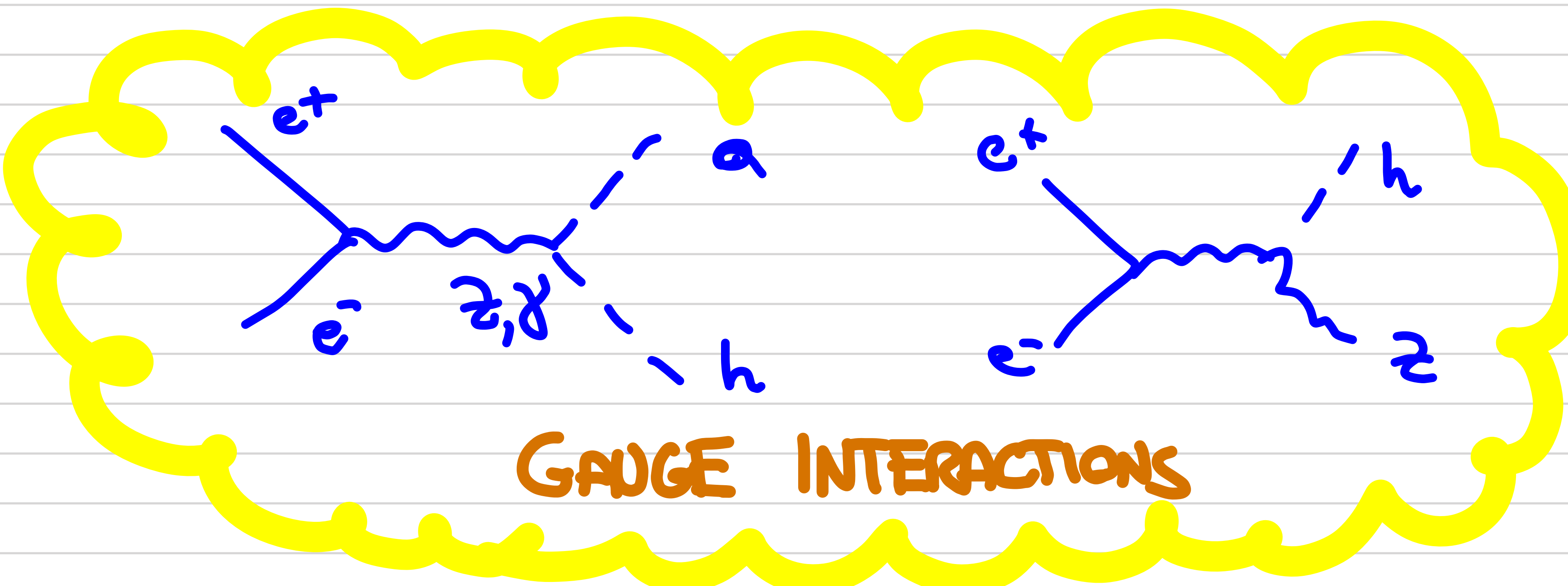
$$\mathcal{M}^2 \sim \begin{pmatrix} m_i^2 & \delta \\ \delta & m_j^2 \end{pmatrix}$$

HIGGS MASS IS PUSHED UP BY THE MIXING

PUSH-UP SCENARIO



← LEP: $S_1 \simeq S$ GAUGE SINGLET



$0 < m < 80$ GeV $\qquad \sin^2\theta \simeq 10^{-2}$

$80 \text{ GeV} < m < 100$ GeV $\qquad \sin^2\theta \simeq 0.1$

$100 \text{ GeV} < m < 110$ GeV $\qquad \sin^2\theta \simeq 0.4$

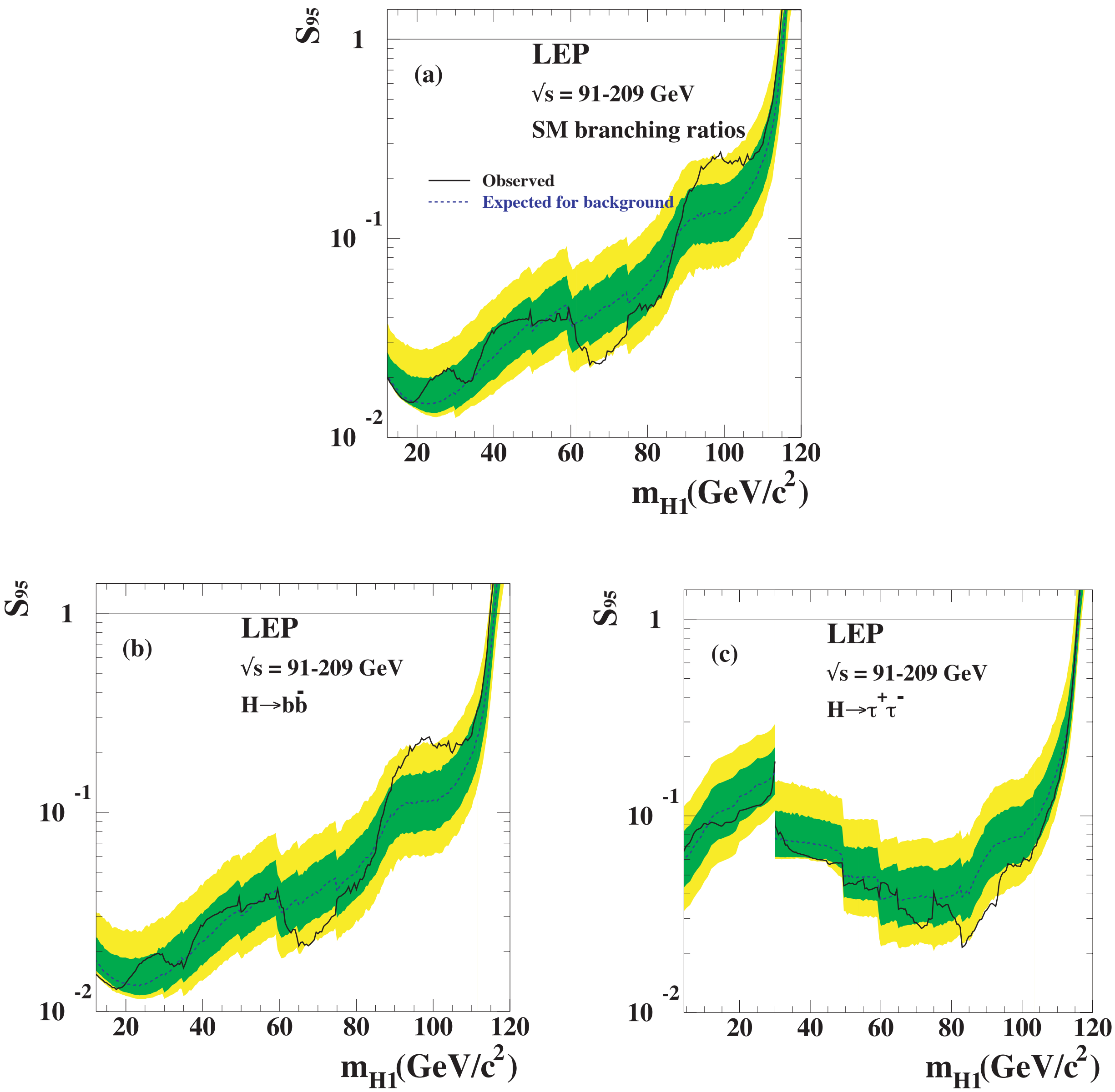
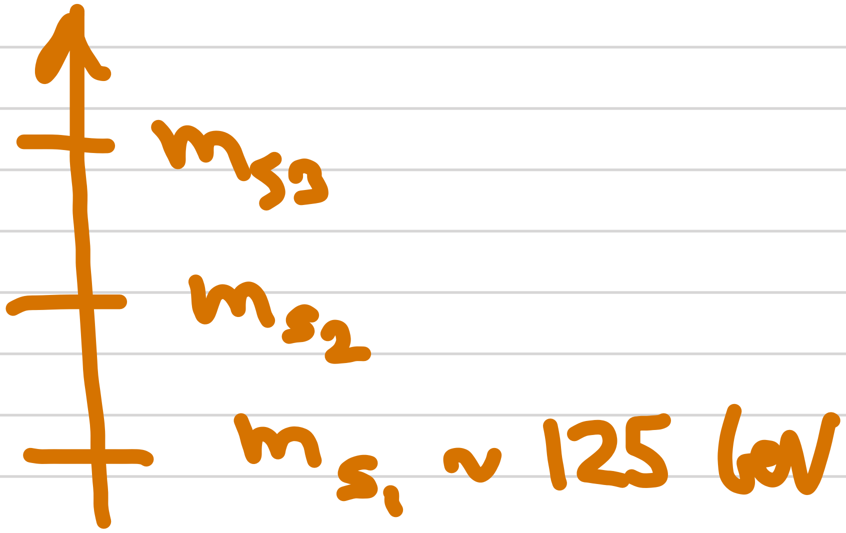


Figure 2: *The 95% CL upper bounds,* S_{95} *(see text), for various topological cross-sections motivated by the Higgsstrahlung process* $e^+e^- \to \mathcal{H}_1 Z$*, as a function of the Higgs boson mass (the figure is reproduced from Ref. [3]). The full lines represent the observed limits. The dark (green) and light (yellow) shaded bands around the median expectations (dashed lines) correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model cross-sections. In part (a) the Higgs boson decay branching ratios are assumed to be those predicted by the Standard Model; in part (b) the Higgs boson is assumed to decay exclusively to* $b\bar{b}$ *and in part (c) exclusively to* $\tau^+\tau^-$*.*

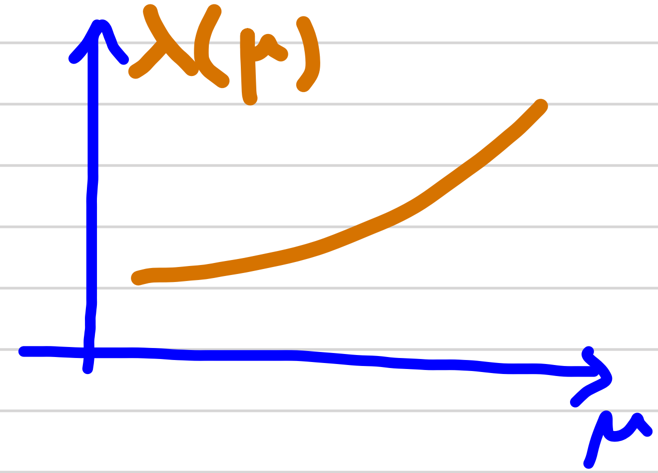
PULL-DOWN SCENARIO

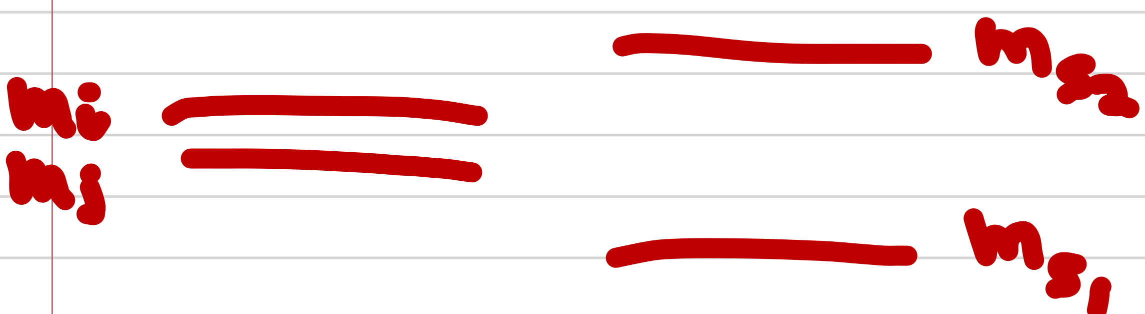


$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

$$\frac{d\lambda}{d\log\mu} \sim \lambda(\lambda^2 - g^2)$$

$$\mathcal{M}^2 \sim \begin{pmatrix} m_i^2 & \delta \\ \delta & m_j^2 \end{pmatrix}$$

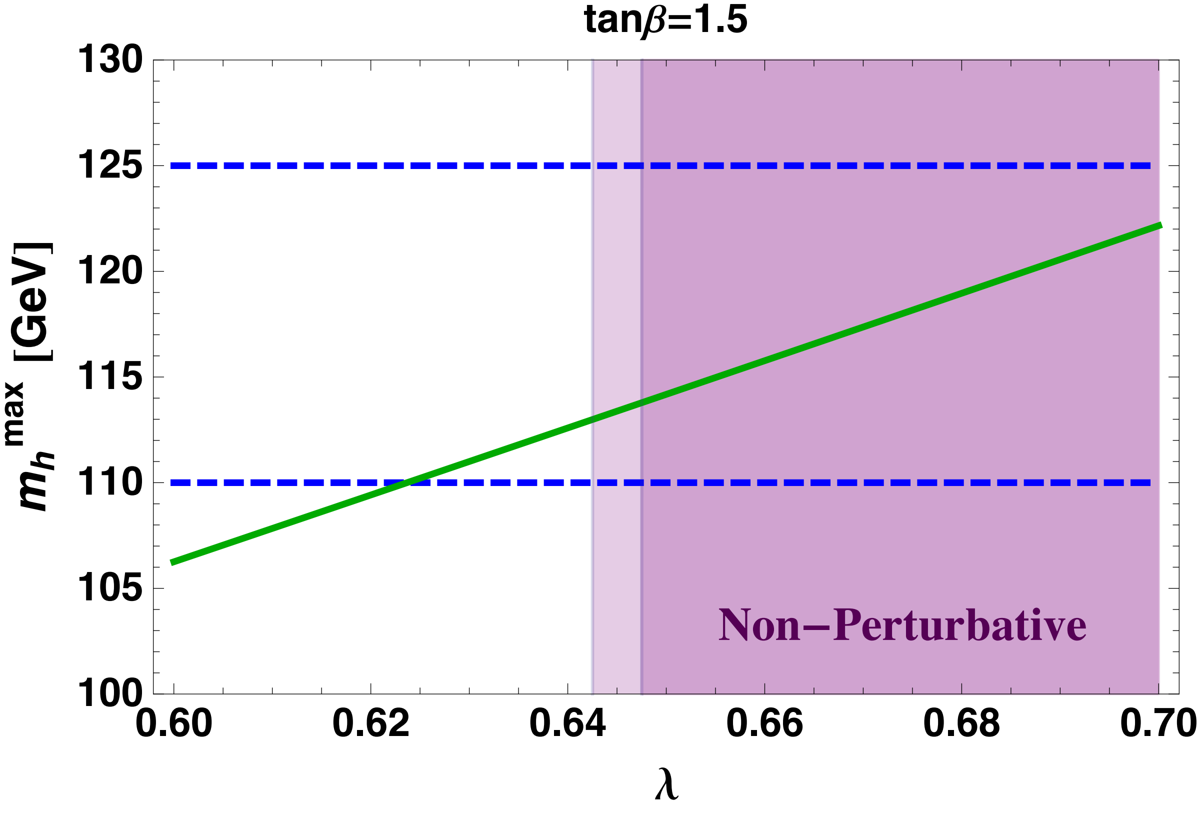




HIGGS MASS IS
<u>PULLED DOWN</u>
BY THE MIXING

AT THE WEAK SCALE:

$$\lambda \lesssim 0.7$$



tanβ=1.5
130
125
120
115
110
105
100
0.60
0.62
0.64
0.66
0.68
0.70
m_h^{max} [GeV]
λ
Non−Perturbative

m_{s_2}

$m_{s_1} \sim 125$ GeV — PERTURBATIVITY till GUT

$m_{s_2} \sim 125$ GeV — LEP SEARCHES

m_{s_1}

CONSTRAIN THE TWO SCENARIOS

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{loop}$$
$$\lambda^2 v^2 \sin^2 2\beta + \delta m^2_{mix}$$

CONSTRAINED ↗

$$\delta m^2_{mix} \sim 2\lambda s v(\lambda - k) + \lambda A_\lambda v$$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{loop}$$

$$\lambda^2 v^2 \sin^2 2\beta + \delta m^2_{mix}$$

δm_{mix} NEEDS TO BE SMALL $\lesssim 0.1$

$$\delta m^2_{mix} \sim 2\lambda s v(\lambda - \kappa) + \lambda A_\lambda v$$

IN GENERAL MANY PARAMETERS PARTICIPATE

$$\Delta_{mix} \equiv \max_i \frac{d \log \delta m^2_{mix}}{d \log p_i}$$

$p_i = \lambda, \kappa, A_\lambda, A_\kappa, \mu$

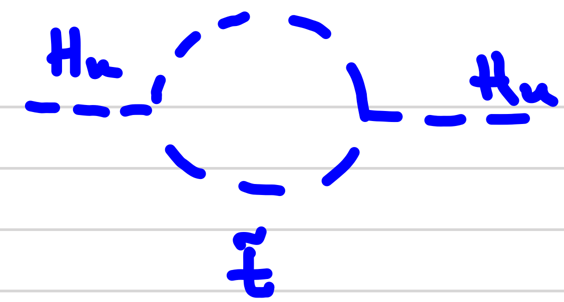
$$\begin{pmatrix} \text{PUSH-UP} \\ \text{PULL-DOWN} \end{pmatrix} \otimes \begin{pmatrix} \lambda < 0.7 \\ \lambda \gtrsim 0.7 \end{pmatrix} \otimes \begin{pmatrix} A_{\lambda,k} \lesssim m_Z \\ A_{\lambda,k} \text{ free} \end{pmatrix}$$

- OTHER LIGHT STATES AT LEP/LHC ?
- PERTURBATIVE UP TO GUT ?
- SUSY BREAKING SCENARIO

$$\begin{pmatrix} \lambda \simeq k \\ \lambda \lesssim k \\ k \ll \lambda \end{pmatrix}$$

- WHAT KIND OF UV COMPLETION ?
- HIGGS SECTOR PHENOMENOLOGY

$$m_Z^2 = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$



$$\delta m_{H_u}^2 \Big|_{stop} \simeq -\frac{3 y_t^2}{8\pi^2} \log \frac{\Lambda_{SUSY}}{TeV} \left(m_{u_3}^2 + m_{Q_3}^2 + |A_t|^2 \right)$$

$\Lambda_{SUSY} \sim 10$ TeV

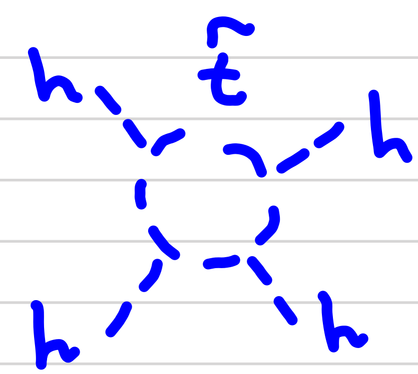
CANCELLATION $\lesssim 20\%$.

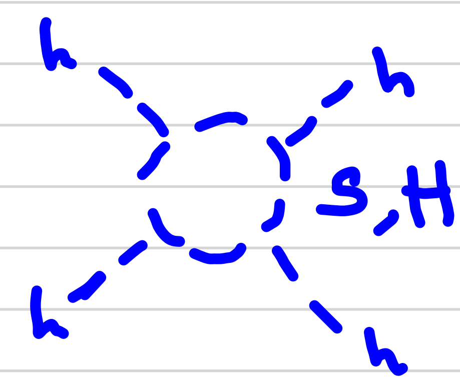
$m_{\tilde t} < 500$ GeV TO NOT REQUIRE LARGE CANCELLATIONS

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{loop} + \lambda^2 v^2 \sin^2 2\beta + \delta m^2_{mix}$$

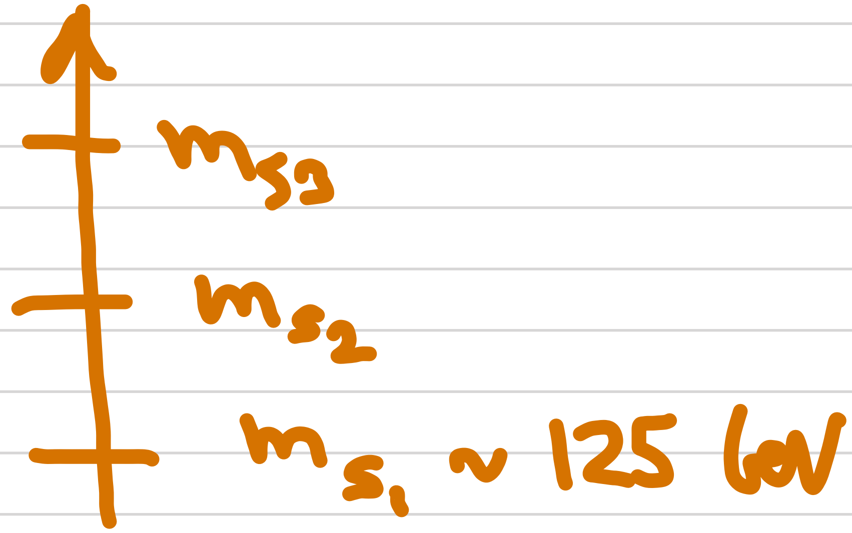
$$= m_{tree}^2 + m_{loop}^2$$

$m_{tree} \geq 110$ GeV



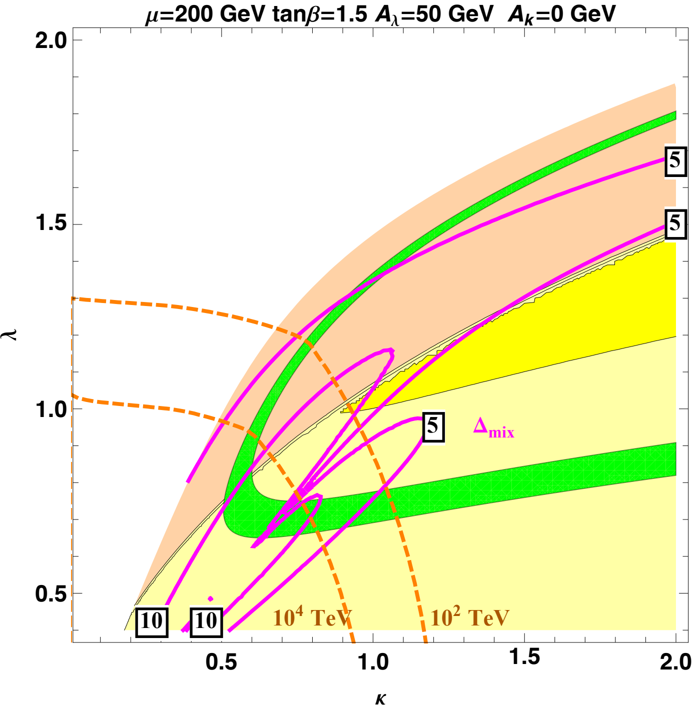


PULL-DOWN



1) $A_{\lambda,k} \simeq 0$

2) $A_{\lambda,k}$ FREE



μ=200 GeV tanβ=1.5 Aλ=50 GeV Ak=0 GeV
λ
κ
2.0
1.5
1.0
0.5
0.5
1.0
1.5
2.0
5
5
5
Δmix
10
10
10^4 TeV
10^2 TeV

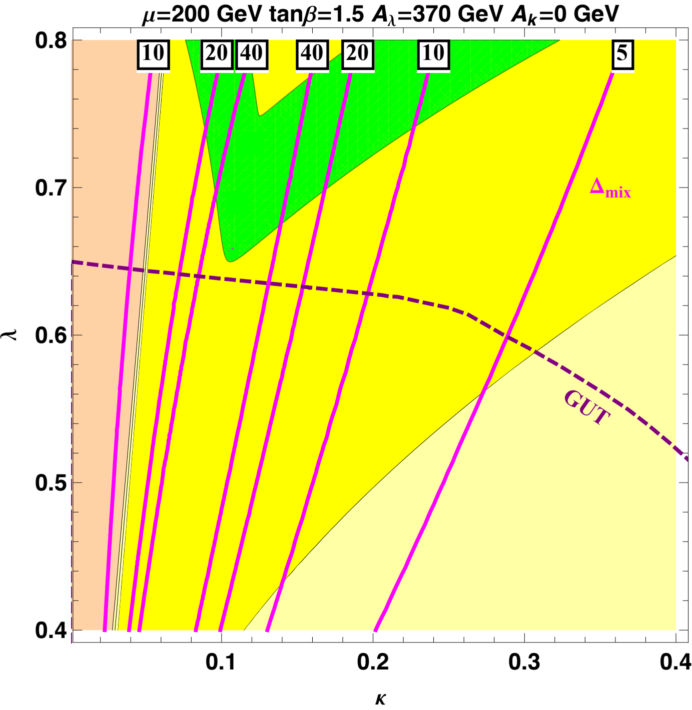
NEGLIGIBLE A-terms $A_{\lambda,k}$

- NO REGION IS COMPATIBLE WITH PERTURBATIVITY UP TO GUT SCALE

- $\lambda \simeq k$ OR $\lambda \lesssim k$ Larsen, Nomura, Roberts - arXiv:1202.6339
  - non-tuned regions exist
  - Higgs couplings may deviate significantly from SM-like
  - low Landau pole (NLSP pheno in GM)

$$\delta m^2_{mix} \sim 2\lambda s v(\lambda - \kappa) + \lambda A_\lambda v$$

SMALL MIXING BY $A_\lambda \simeq 2\mu$

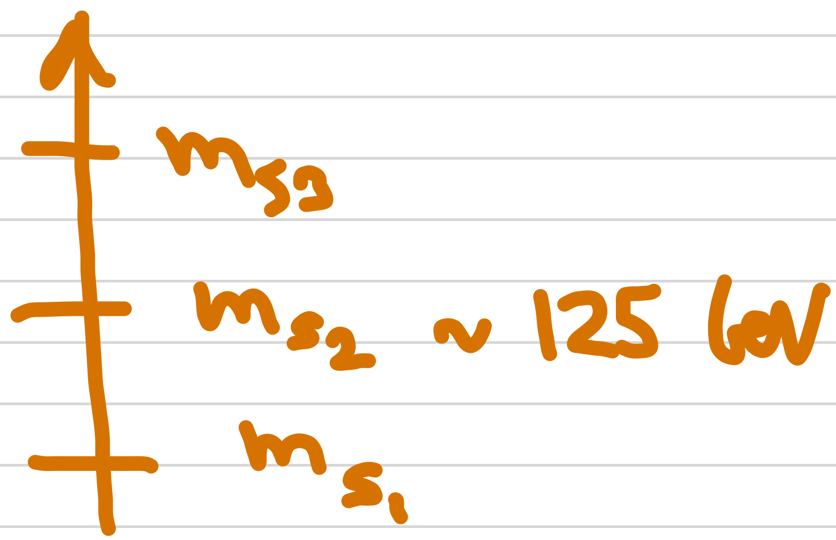


μ=200 GeV tanβ=1.5 A_λ=370 GeV A_k=0 GeV
10
20
40
40
20
10
5
Δ_{mix}
GUT
0.8
0.7
0.6
0.5
0.4
λ
0.1
0.2
0.3
0.4
κ

SMALL MIXING BY $A_\lambda \simeq 2\mu$

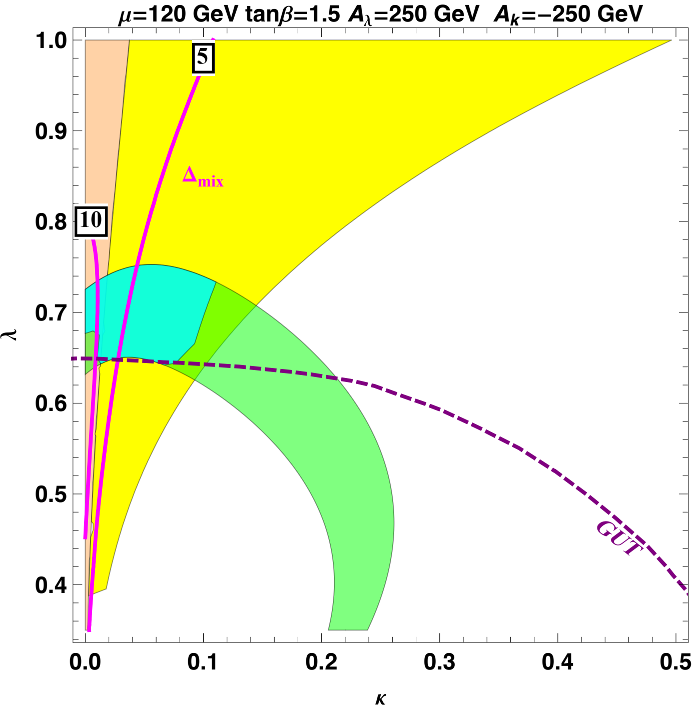
- TENSION BETWEEN PERTURBATIVITY UP TO GUT AND m_h
- TUNED BY $A_\lambda = 2\mu$ UP TO 1%.
- $\kappa, \lambda, A_\lambda, A_\kappa, \mu$ QUITE FIXED

PUSH-UP



BEST SCENARIO FOR PERTURBATIVITY

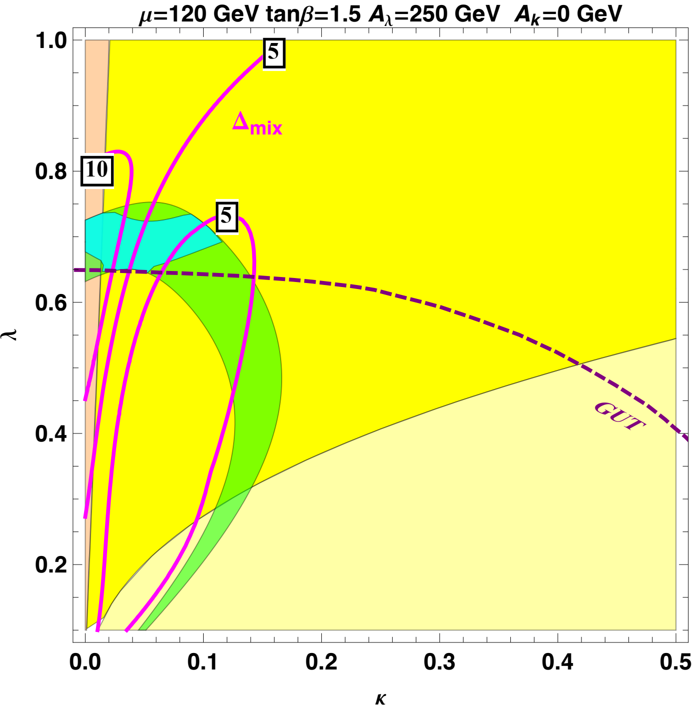
A_{λ_k} FREE (to be ok with LEP)



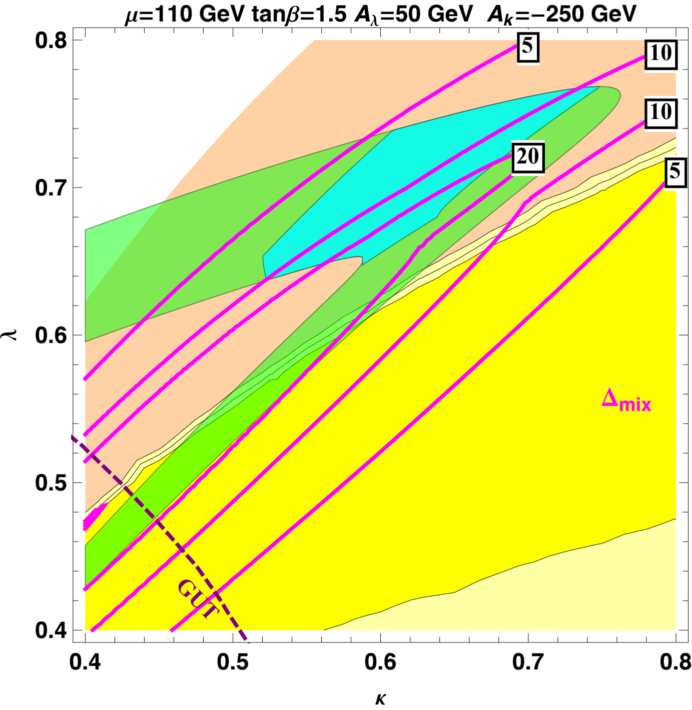
μ=120 GeV tanβ=1.5 A_λ=250 GeV A_k=−250 GeV
1.0
0.9
0.8
0.7
0.6
0.5
0.4
λ
0.0
0.1
0.2
0.3
0.4
0.5
κ
5
10
Δ_{mix}
GUT

$A_{\lambda,\kappa} \neq 0$ PUSH-UP

- NON-TUNED REGION
- SOME TENSION WITH PERTURBATIVITY
- $\kappa, \lambda, A_\lambda, A_\kappa, \mu$ QUITE FIXED



μ=120 GeV tanβ=1.5 A_λ=250 GeV A_k=0 GeV
1.0
0.8
0.6
0.4
0.2
λ
0.0
0.1
0.2
0.3
0.4
0.5
κ
5
10
5
Δ_{mix}
GUT



μ=110 GeV tanβ=1.5 Aλ=50 GeV Ak=−250 GeV
0.8
0.7
0.6
0.5
0.4
λ
κ
5
10
10
20
5
Δmix
GUT

$A_k \neq 0$ PUSH-UP

- SIGNIFICANT TUNING TO GET m_h
- NON-PERTURBATIVE
- $\lambda \propto k$

YELLOW, LIGHT YELLOW, RED ...

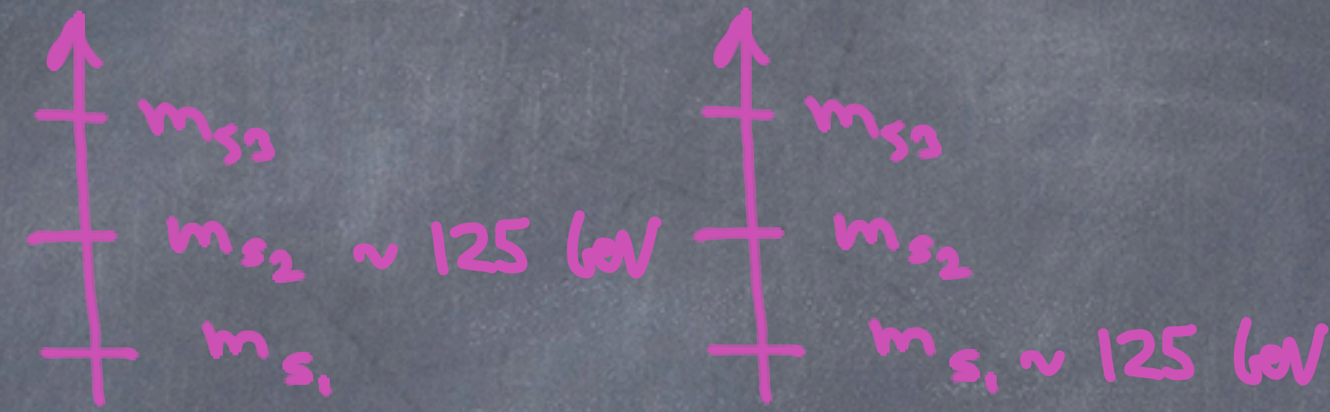
WHEN THE NMSSM SOFT MASSES OR COUPLINGS ARE LARGE $A_\lambda, A_k, \lambda, k$ THE HIGGS POTENTIAL CAN DEVELOP EXTRA MINIMA WHERE EWSB IS NOT CORRECT

$v \neq \frac{m_W}{g}$ $\quad s \neq \frac{\mu}{\lambda}$

- REQUIRE MORE WORK (LIFETIME)
- PUSH-UP CAN BE OK
- PULL-DOWN CAN HAVE TROUBLES (LARGE λ)

CONCLUSIONS

- BOTH PULL-DOWN AND PUSH-UP ARE VIABLE



  PUSH-UP BETTER FOR PERTURBATIVITY

- LIGHTER AND HEAVIER HIGGS BOSONS WITH OBSERVABLE LHC PHENO + HIGGS COUPLINGS

- PARAMETERS SPACE IS REDUCED TO FEW REGIONS OF INTEREST $\lambda \sim k$ $A_\lambda \sim 2\mu$

- VACUUM STABILITY MAY BE AN ISSUE

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ArXiv:1209.2115
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