PRECISION MEASUREMENTS OF HIGGS/HIGGSINOS

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based on
Phys.Rev. D92 (2015) no.3, 035006,
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with H. Baer, N. Nagata and H. Serce

@HU-IBS Summer Institute

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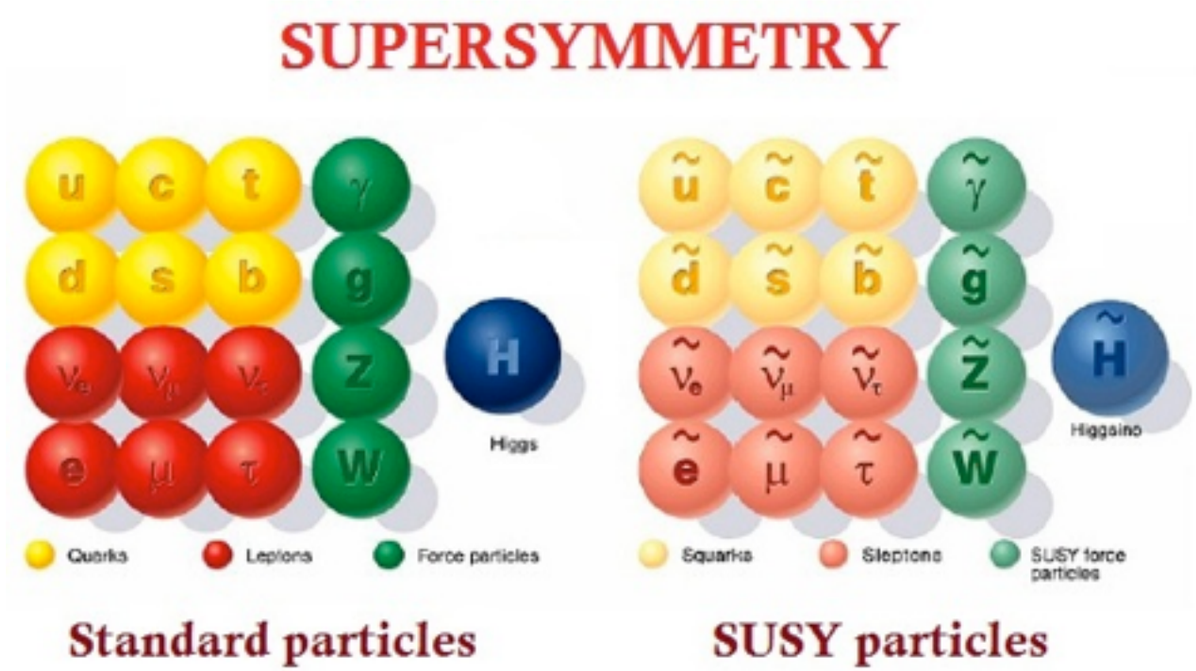
SUPERSYMMETRY

- motivated by "*Naturalness*", solving gauge hierarchy problem.
- successful gauge coupling unification
- "weak scale SUSY" provides natural electroweak symmetry breaking.
- weak scale dark matter candidates

MINIMAL EXTENSION

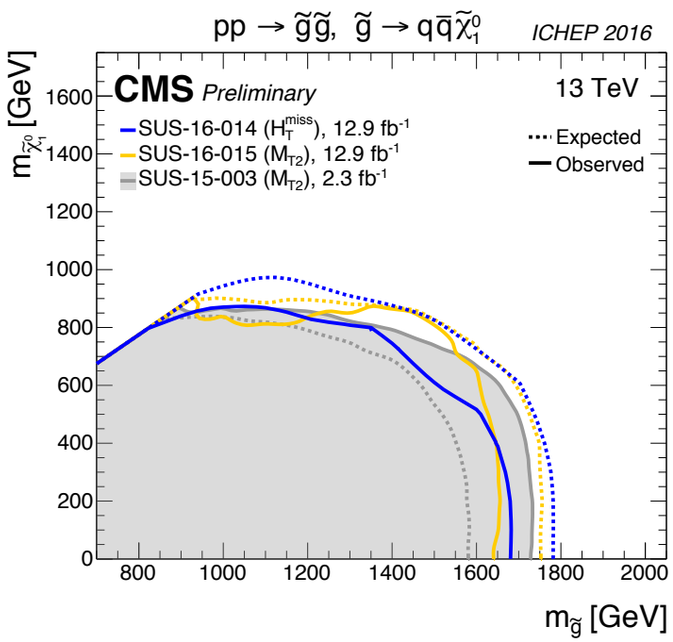


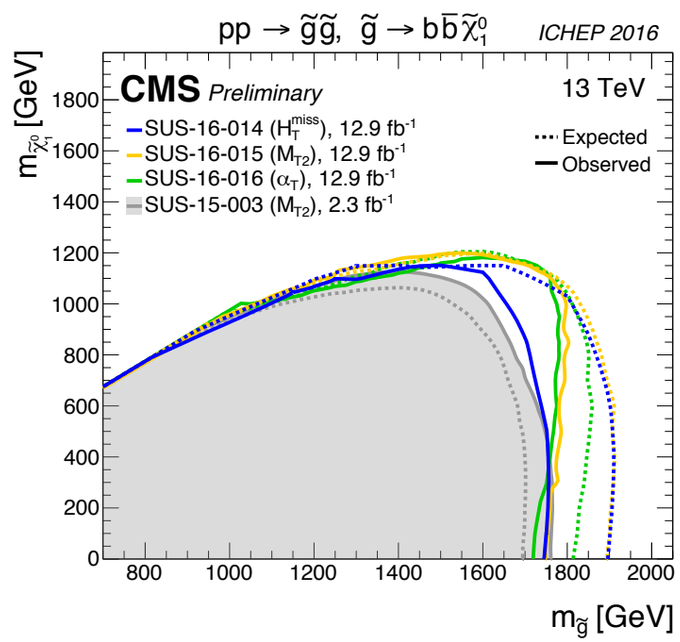
- gluinos/squarks: *strongly interacting*, most promising at hadron colliders
- Bino, Wino, **Higgsinos**, sleptons: weakly interacting, hard to find at hadron colliders, possibly discovered at lepton colliders
- New **Higgs** states: 2 Higgs doublets, additional heavy Higgs states $H, A, H^{\pm}$

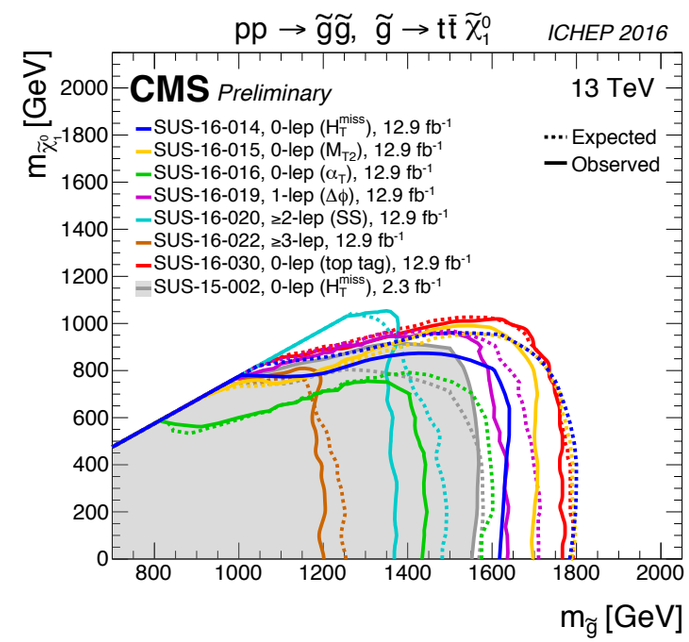
SUSY @ LHC-13 (I)

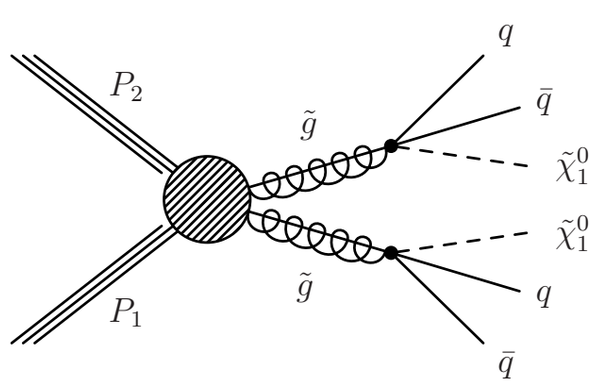
Limits on Direct Gluino Production

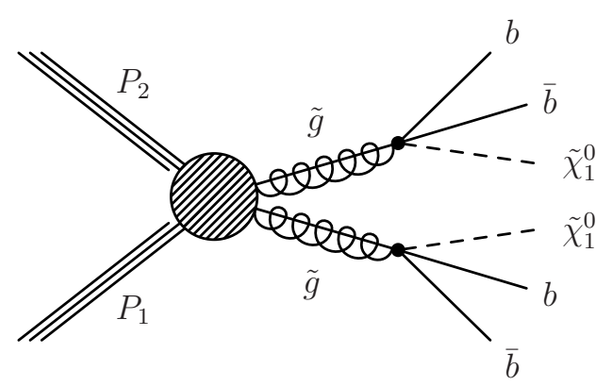
- Excluding **gluinos** up to 1.75 TeV and **neutralinos** up to 1.2 TeV

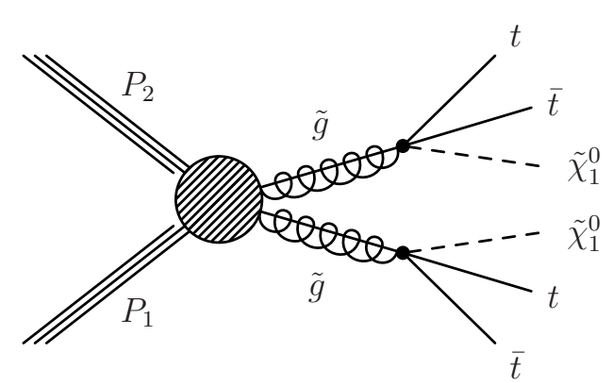










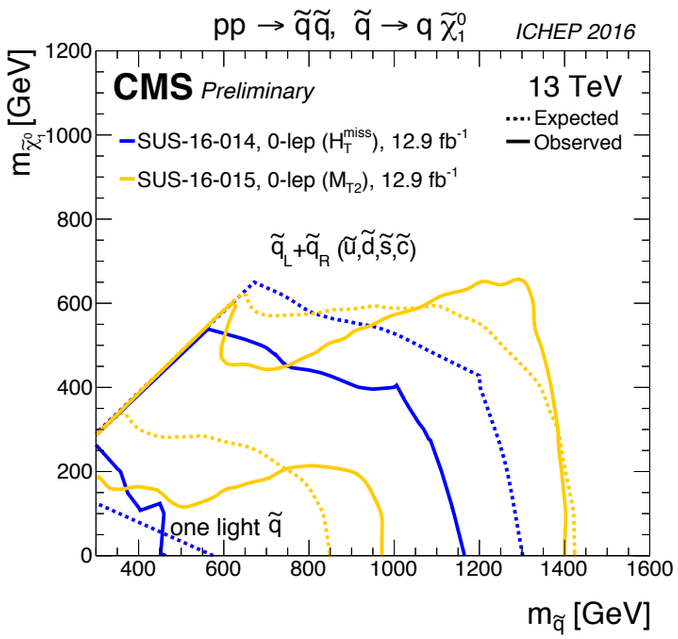


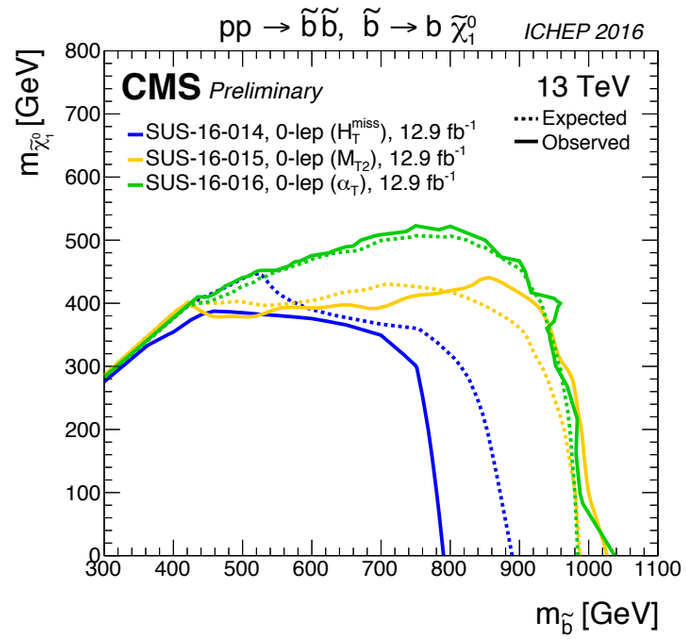
Slide by F. Pandolfi, ICHEP 16

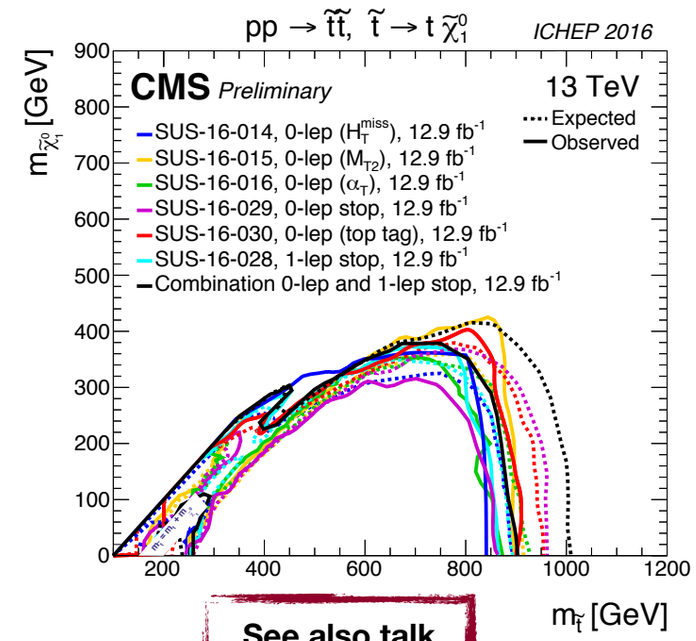
SUSY @ LHC-13 (2)

Limits on Direct Squark Production

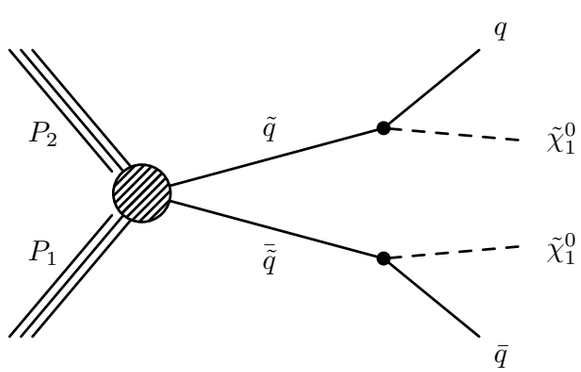
- Excluding **squarks (stops)** up to 1.4 (0.9) TeV and **neutralinos** up to 500 GeV

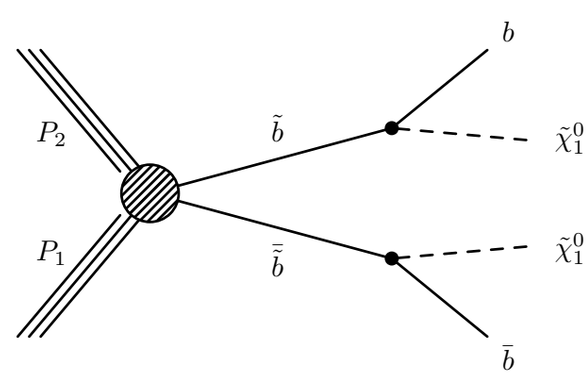


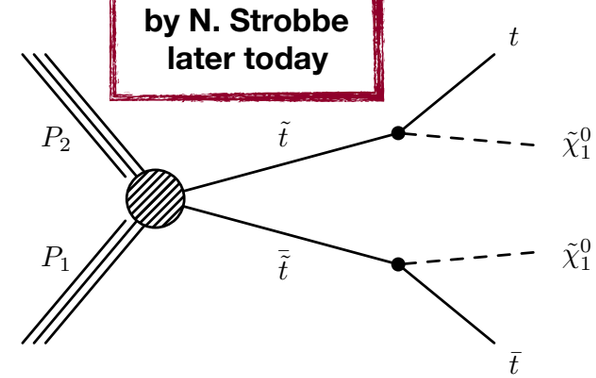




See also talk by N. Strobbe later today







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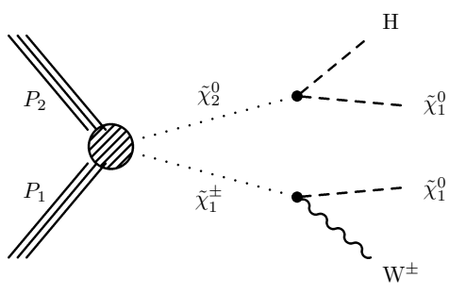
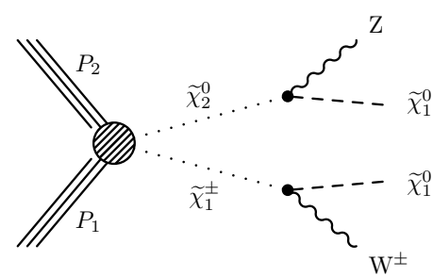
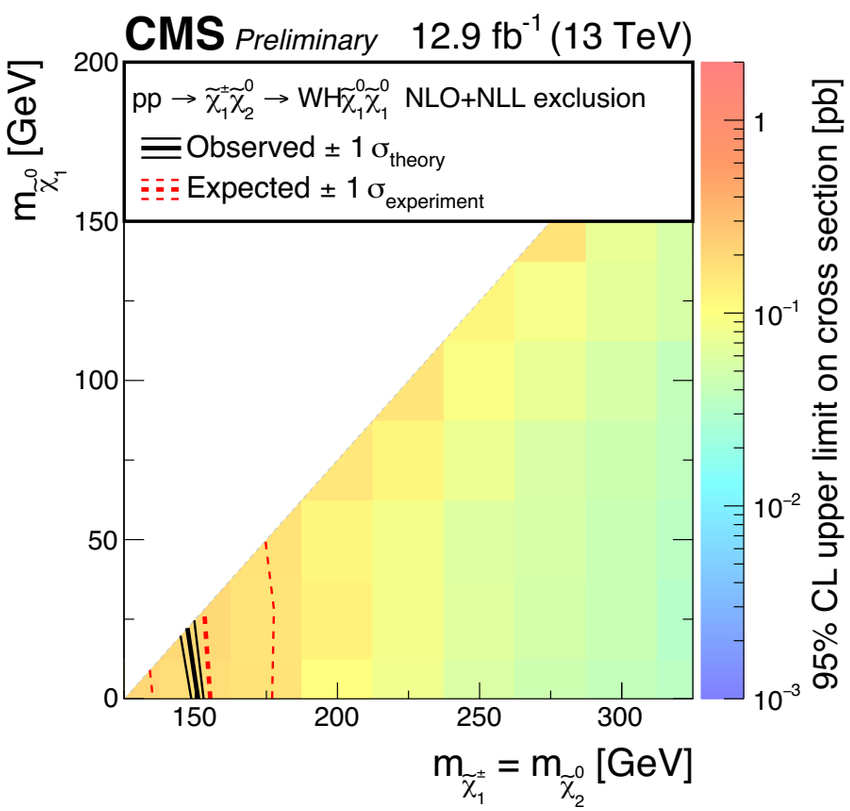
SUSY @ LHC-13 (3)

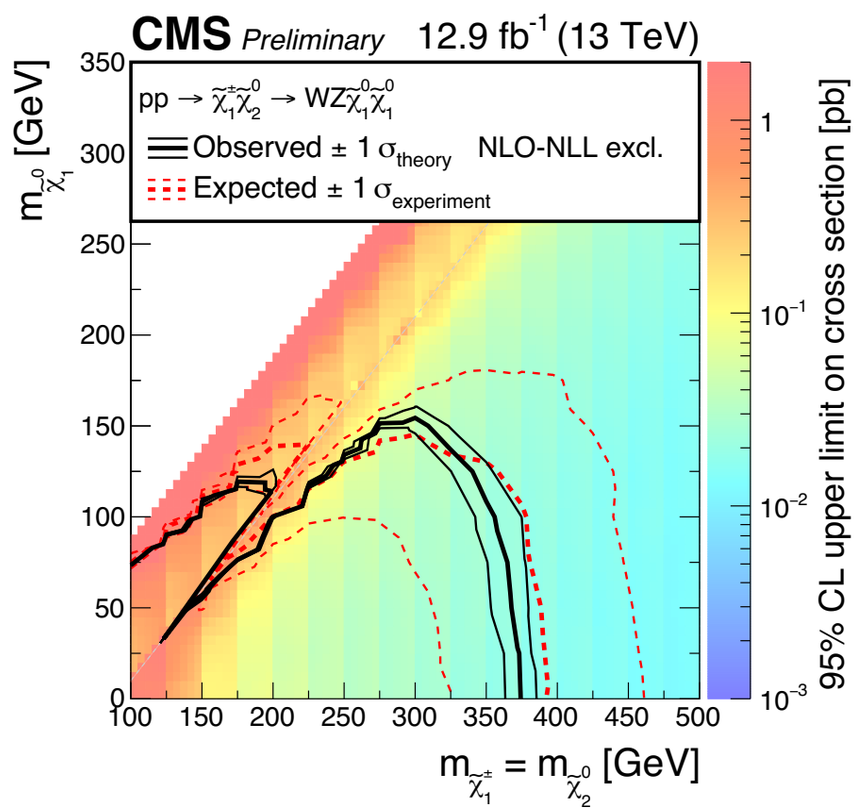
INTERPRETATION (II)

3L signal regions can be interpreted in the context of other chargino-neutralino production, assuming heavy sleptons, decay to W,Z and h bosons.







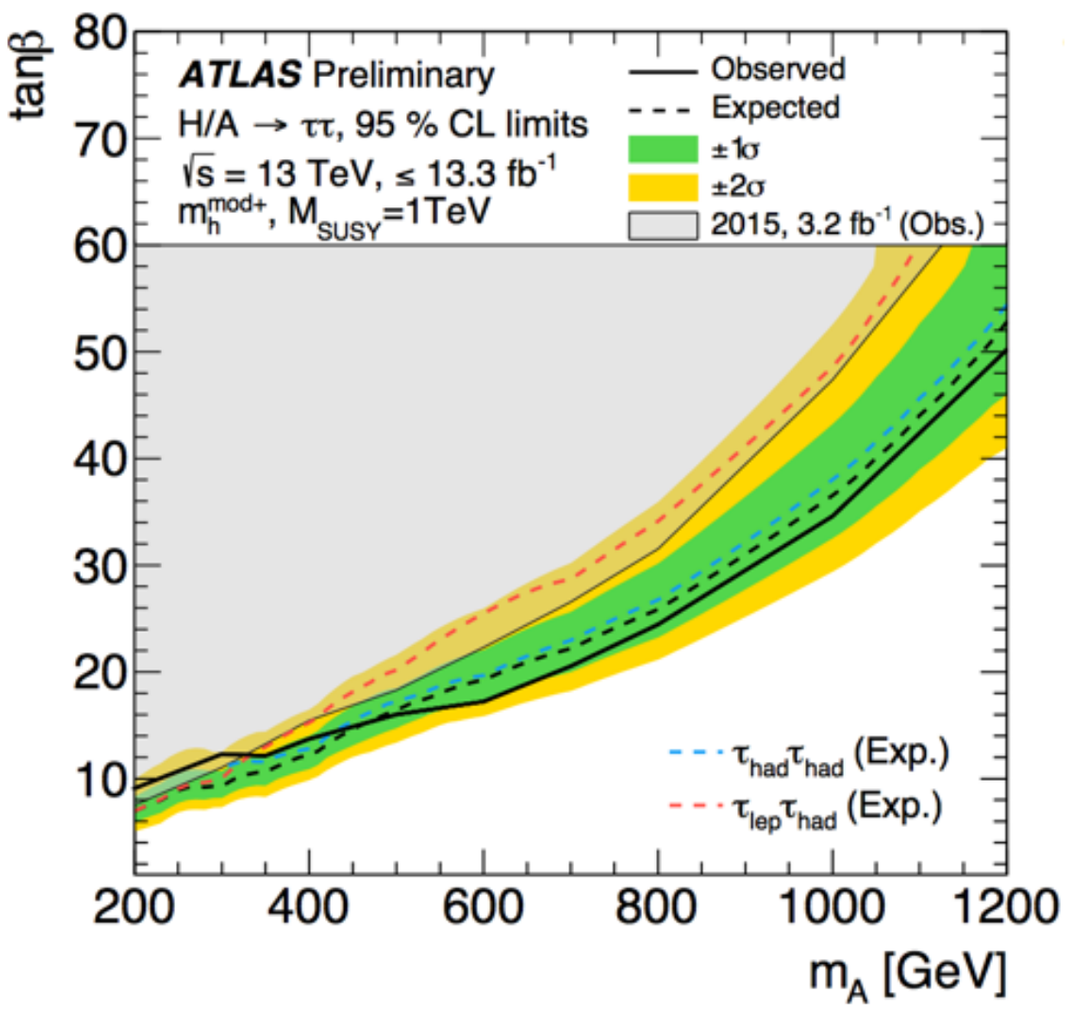


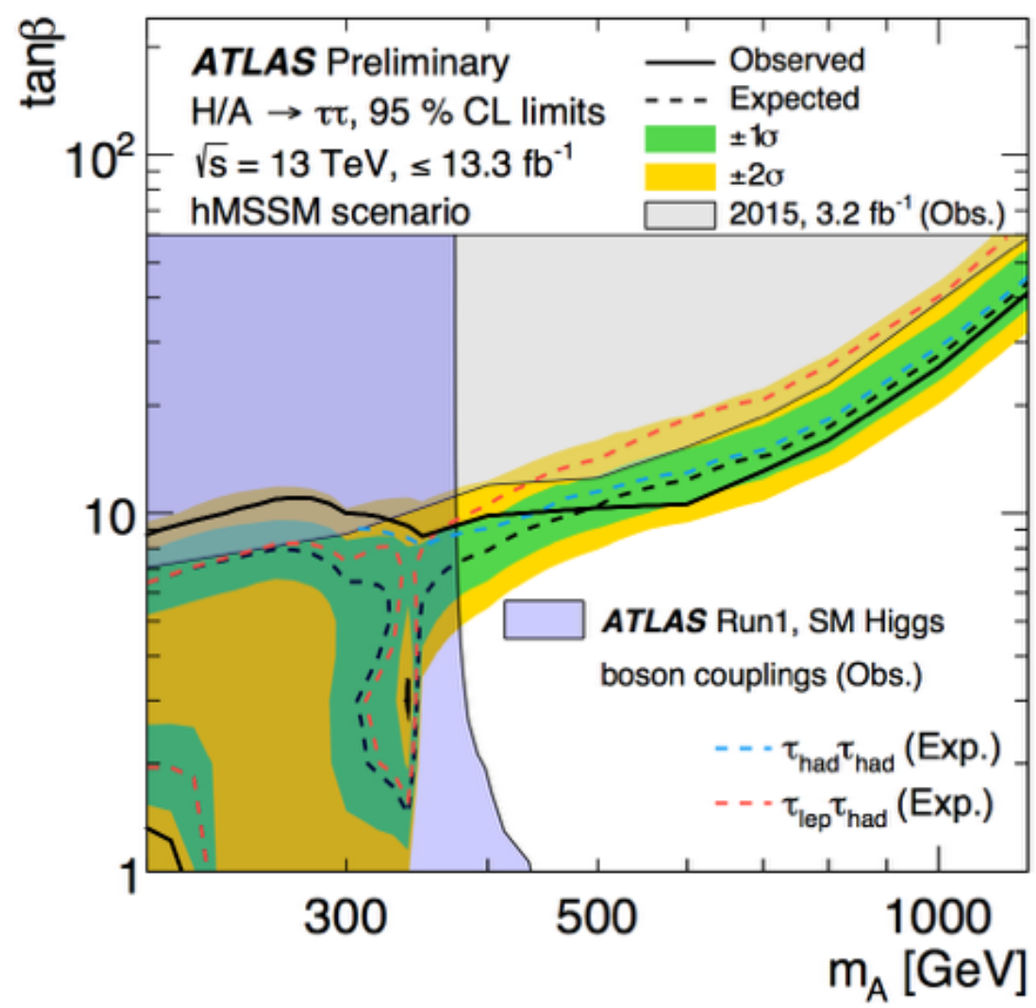
Slide by S. Folgueras, ICHEP 16

HEAVY HIGGSES?

MSSM Neutral Higgs Search ($A/H \rightarrow \tau^+\tau^-$)

- We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios
- In the m_h^{mod+} scenario, we exclude $\tan\beta > 16$ for $m_A = 600$ GeV and $\tan\beta > 35$ for $m_A = 1$ TeV
- In the hMSSM, we have sensitivity to exclude the low m_A-low $\tan\beta$ corner and the island around 350 GeV. Note: the features around 350 GeV are related to the $\sigma \times$ BR evolution near the $A/H \rightarrow$ ttbar threshold
- hMSSM plot shows Run-1 couplings exclusion (κ_V, κ_u and κ_d)





Slide by T. Vickey, ICHEP 16

HIGGS & HIGGSINOS

- *Naive hope for SUSY discovery at LHC has been faded.*
- But we could still see

Higgs couplings:

- Higgs couplings can be modified by mixings and/or loop effects of new particles.
- Precision measurements at LHC/ILC will examine coupling deviation from SM predictions.

Light Higgsinos:

- Light Higgsinos are still possible and good for "naturalness."
- Bino/Wino contaminations in neutralino/chargino allow us to see effects of heavy states.

OUTLINE

1. Introduction
2. Precision measurement of Higgs couplings
3. Precision measurement of Higgsino masses
4. Summary

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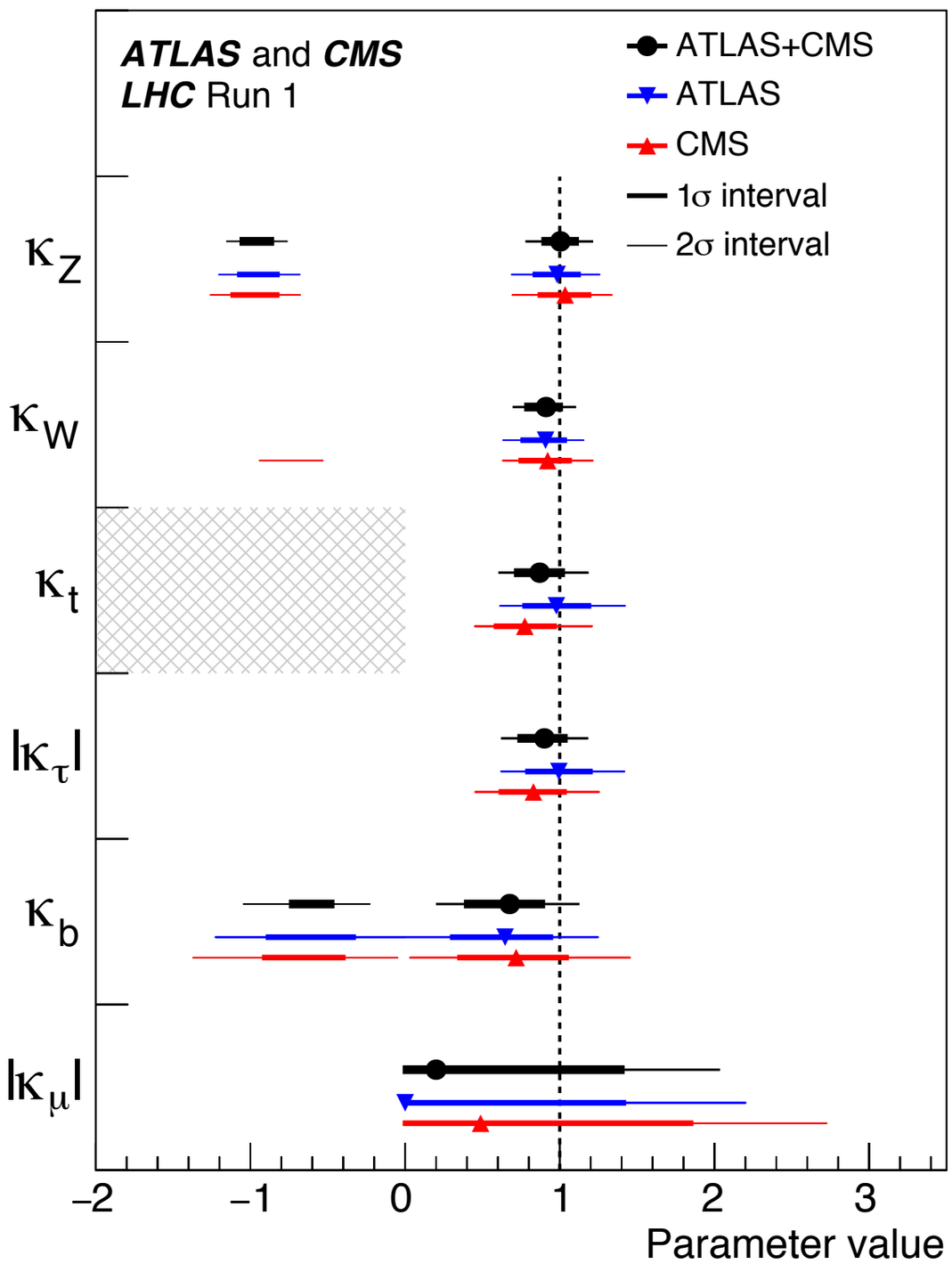
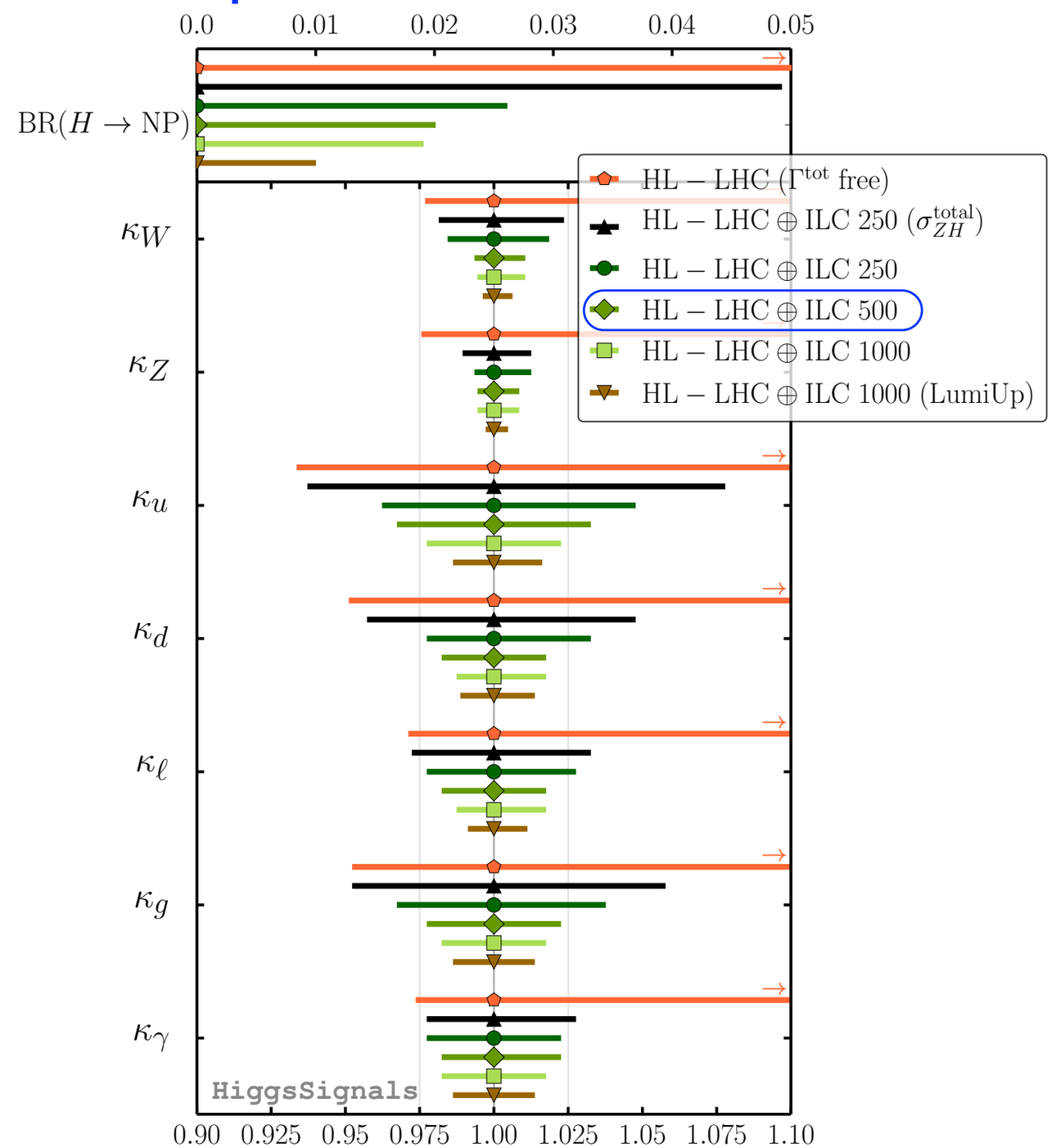
HIGGS COUPLINGS @ COLLIDERS

Current Bound



Expected Bound



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HIGGS IN MSSM

- Higgs mass matrix

$$\mathcal{M}_h^2 = \begin{pmatrix} m_{H_u}^2 + \mu^2 + m_Z^2(1 - 2\cos 2\beta)/2 & -(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 + m_Z^2)\sin 2\beta/2 \\ -(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 + m_Z^2)\sin 2\beta/2 & m_{H_d}^2 + \mu^2 + m_Z^2(1 + 2\cos 2\beta)/2 \end{pmatrix} + \delta\mathcal{M}_h^2$$

diagonalized by

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_{uR}^0 \\ h_{dR}^0 \end{pmatrix}$$

$$(0 \leq \alpha \leq \pi/2)$$

- *In the heavy A limit,* $m_A^2 = m_{H_u}^2 + m_{H_d}^2 + 2\mu^2$

$$\cos(\alpha+\beta) = \frac{m_Z^2 \sin 4\beta}{2m_A^2}\left(1 - \frac{\delta\mathcal{M}_{h,11}^2 - \delta\mathcal{M}_{h,22}^2}{2m_Z^2\cos 2\beta} - \frac{\delta\mathcal{M}_{h,12}^2}{m_Z^2 \sin 2\beta}\right) + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)$$

$$\sin(\alpha+\beta) \simeq 1 - \frac{1}{2}\cos^2(\alpha+\beta) = 1 - \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)$$

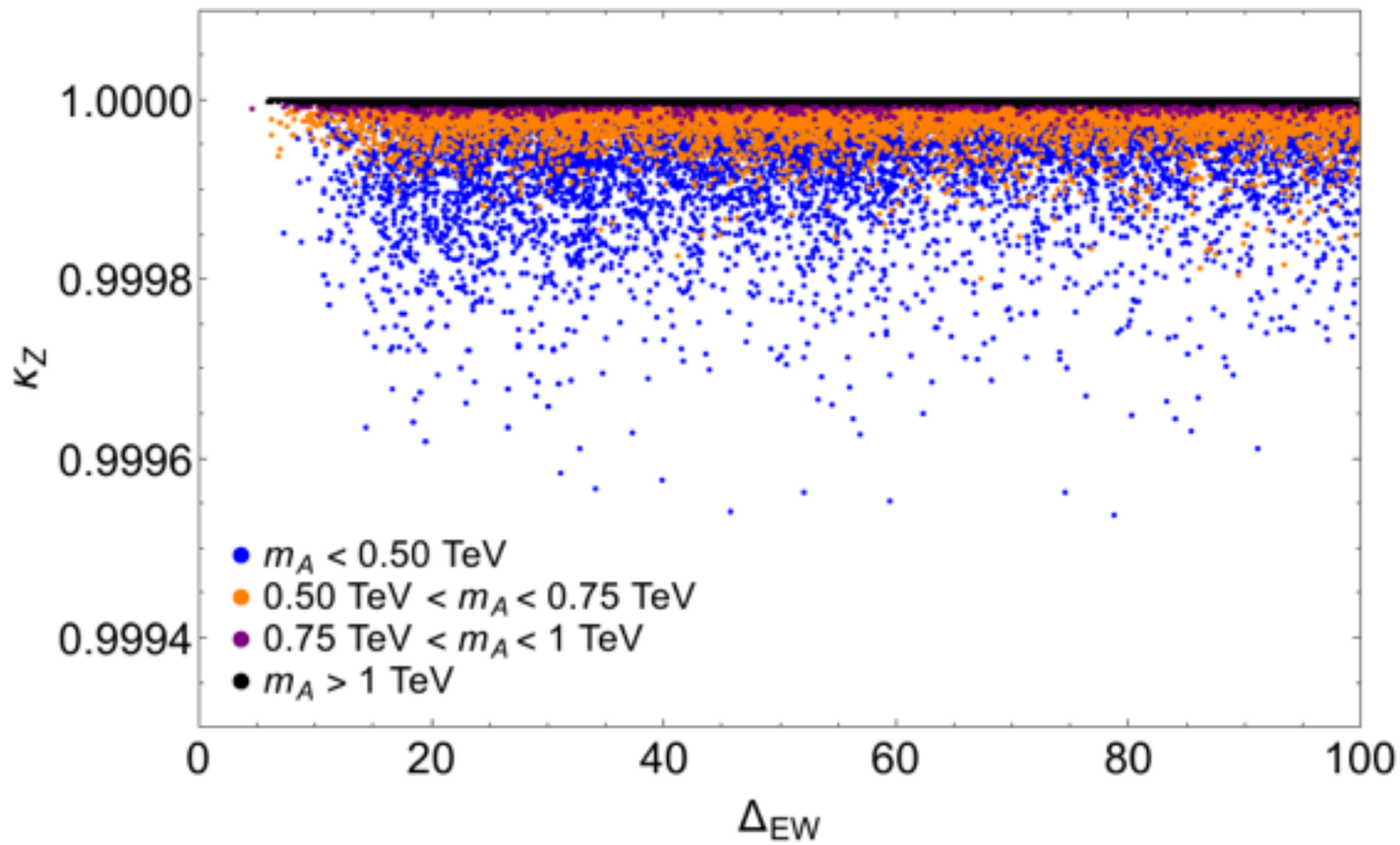
- MSSM/SM coupling ratios are determined by **α** & **β**

H-V-V COUPLING

- *Non-SM coupling from Higgs mixing*

$$g_{hVV} = g_{hVV}^{\rm SM} \sin(\alpha+\beta) \quad \text{for} \quad V = W, Z.$$

$$\kappa = g/g^{\rm SM}$$



- Deviation $\propto \cos^2(\alpha+\beta) \propto m_Z^4/m_A^4$
- Unless m_A is small, it doesn't show a significant deviation; *far less than HL-LHC / ILC500 reach*.

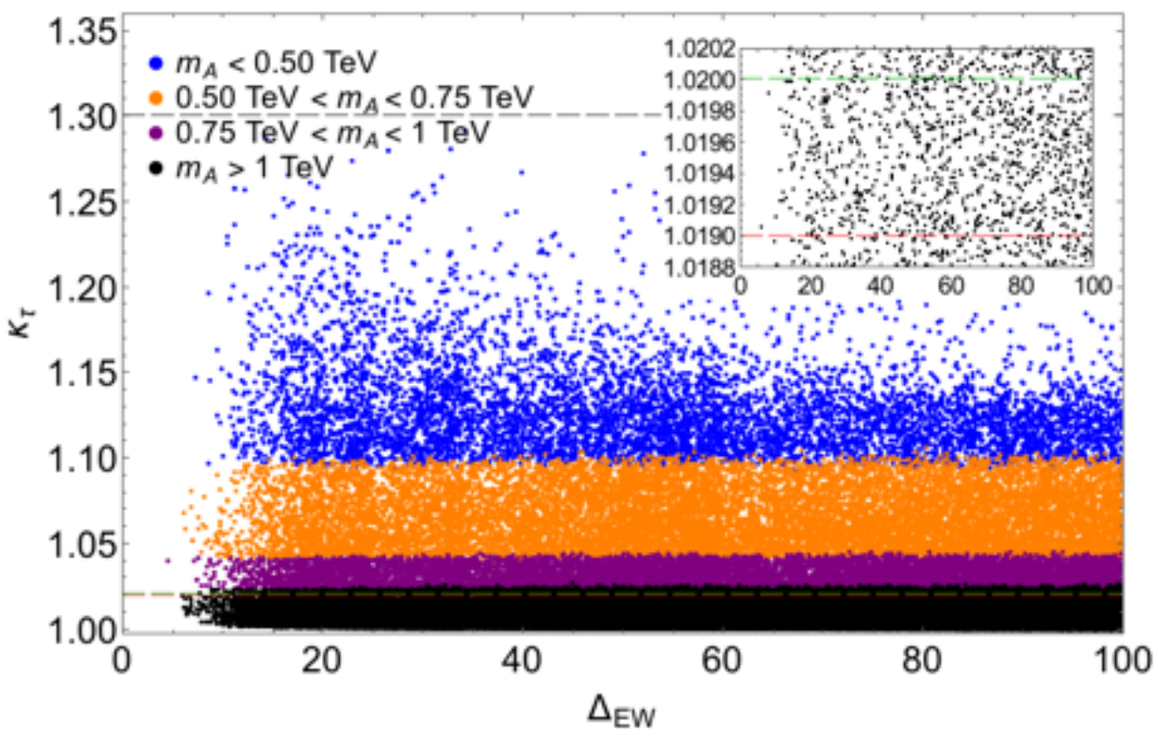
H-F-F COUPLINGS (1)

- *Eff. Lagrangian from RGE & SUSY threshold*

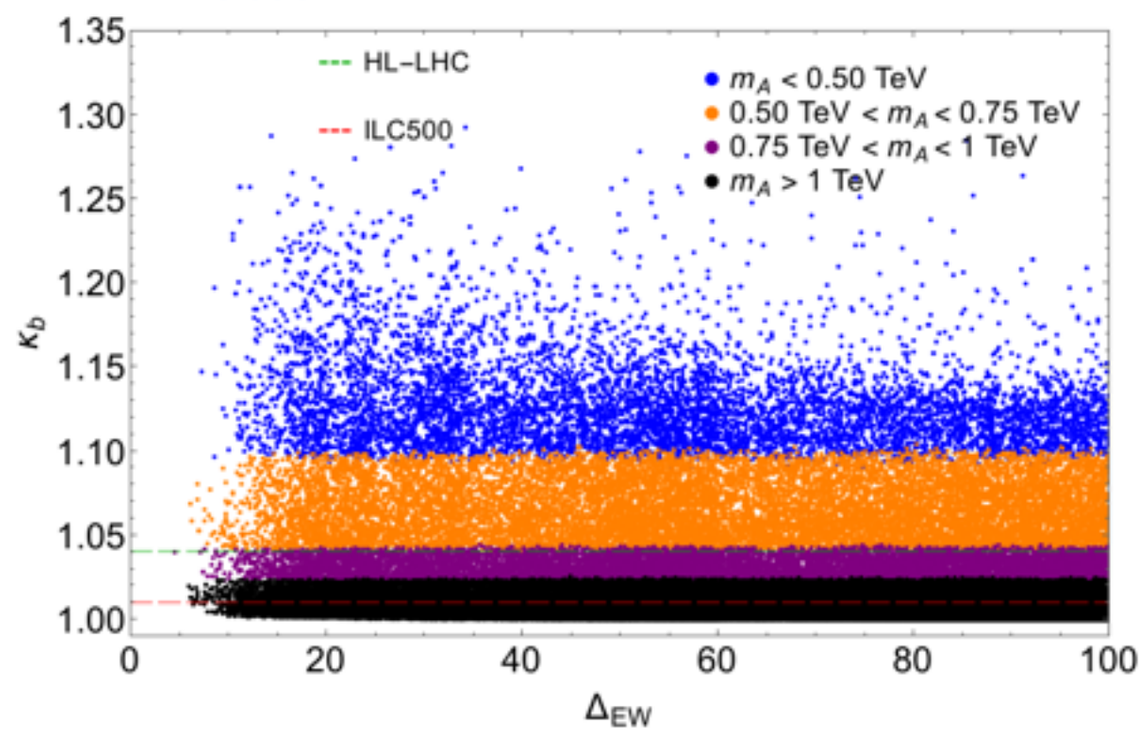
$$-\mathcal{L}_{\rm eff} = (f_b + \delta f_b)\bar{b}_R H_d Q_3 + \Delta f_b \bar{b}_R H_u^* Q_3 + (f_t + \delta f_t)\bar{t}_R H_u Q_3 + \Delta f_t \bar{t}_R H_d^* Q_3 + \text{h.c.}$$

$$\boxed{\begin{aligned} g_{hbb} &= g_{hbb}^{\rm SM}\left[\sin(\alpha+\beta) - \frac{\cos(\alpha+\beta)}{1+\Delta_b}\left\{\tan\beta - \Delta_b\cot\beta + (\tan\beta+\cot\beta)\frac{\delta f_b}{f_b}\right\}\right] \\ g_{htt} &= g_{htt}^{\rm SM}\left[\sin(\alpha+\beta) + \frac{\cos(\alpha+\beta)}{1+\Delta_t}\left\{(1+\Delta_t)\cot\beta - (1+\cot^2\beta)\frac{\Delta f_t}{f_t}\right\}\right] . \end{aligned}}$$

Tau



Bottom



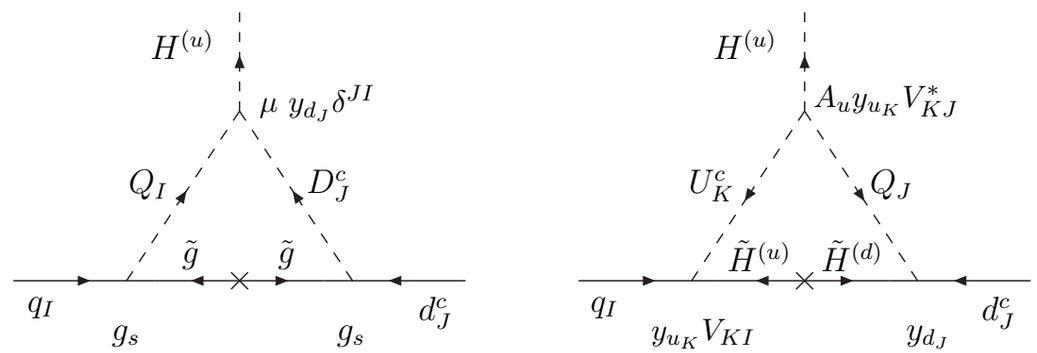
- **B and Tau** coupling: Large deviation for small m_A, probed by HL-LHC /ILC500

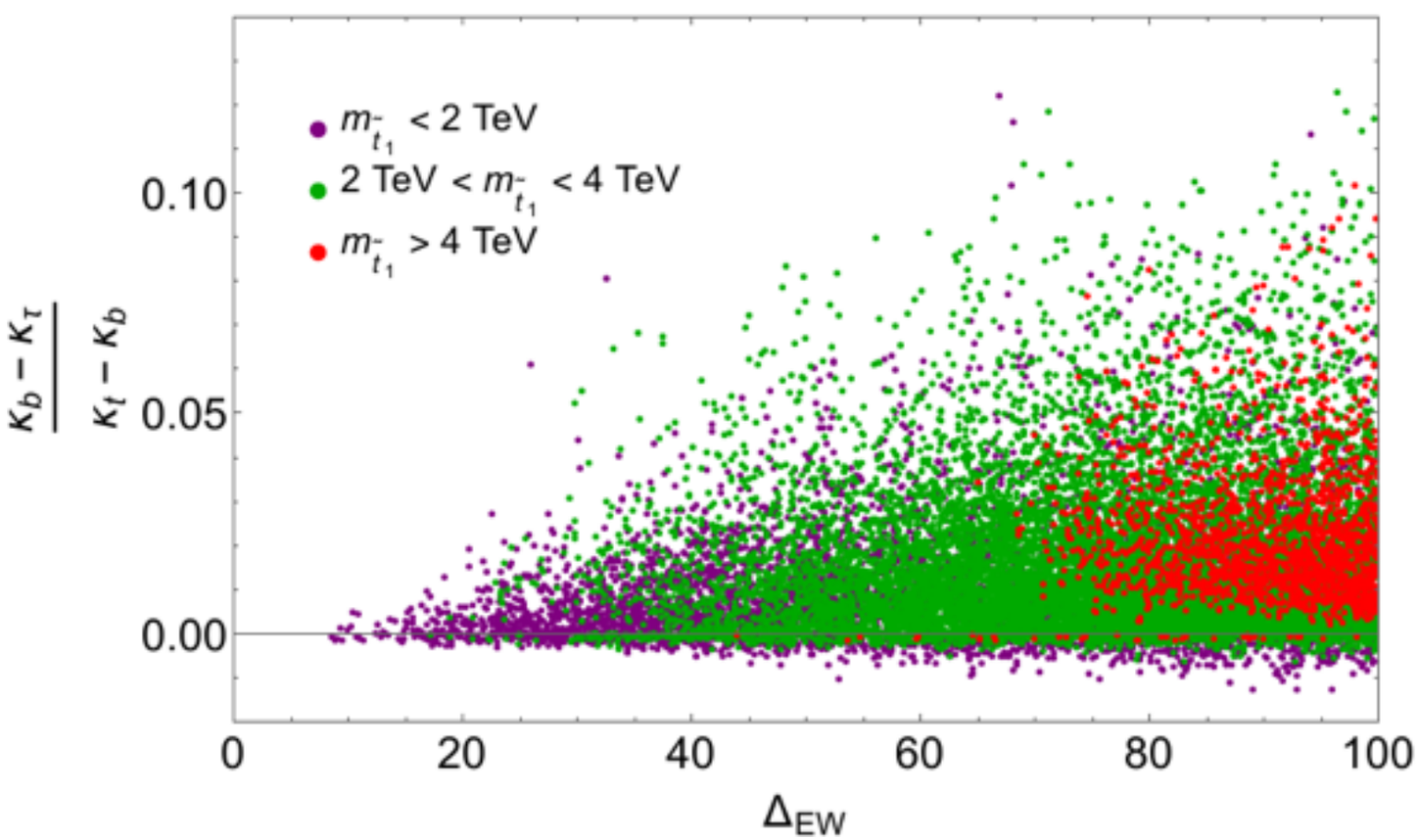
H-F-F COUPLINGS (2)

- *Probing non-holomorphic correction from SUSY threshold*

$$\frac{\kappa_b - \kappa_\tau}{\kappa_t - \kappa_b} \simeq \Delta_b$$

$$\Delta_b \simeq \left[\frac{2\alpha_s}{3\pi} M_3 \mu I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M_3^2) + \frac{f_t^2}{16\pi^2}\mu A_t I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)\right]\tan\beta$$



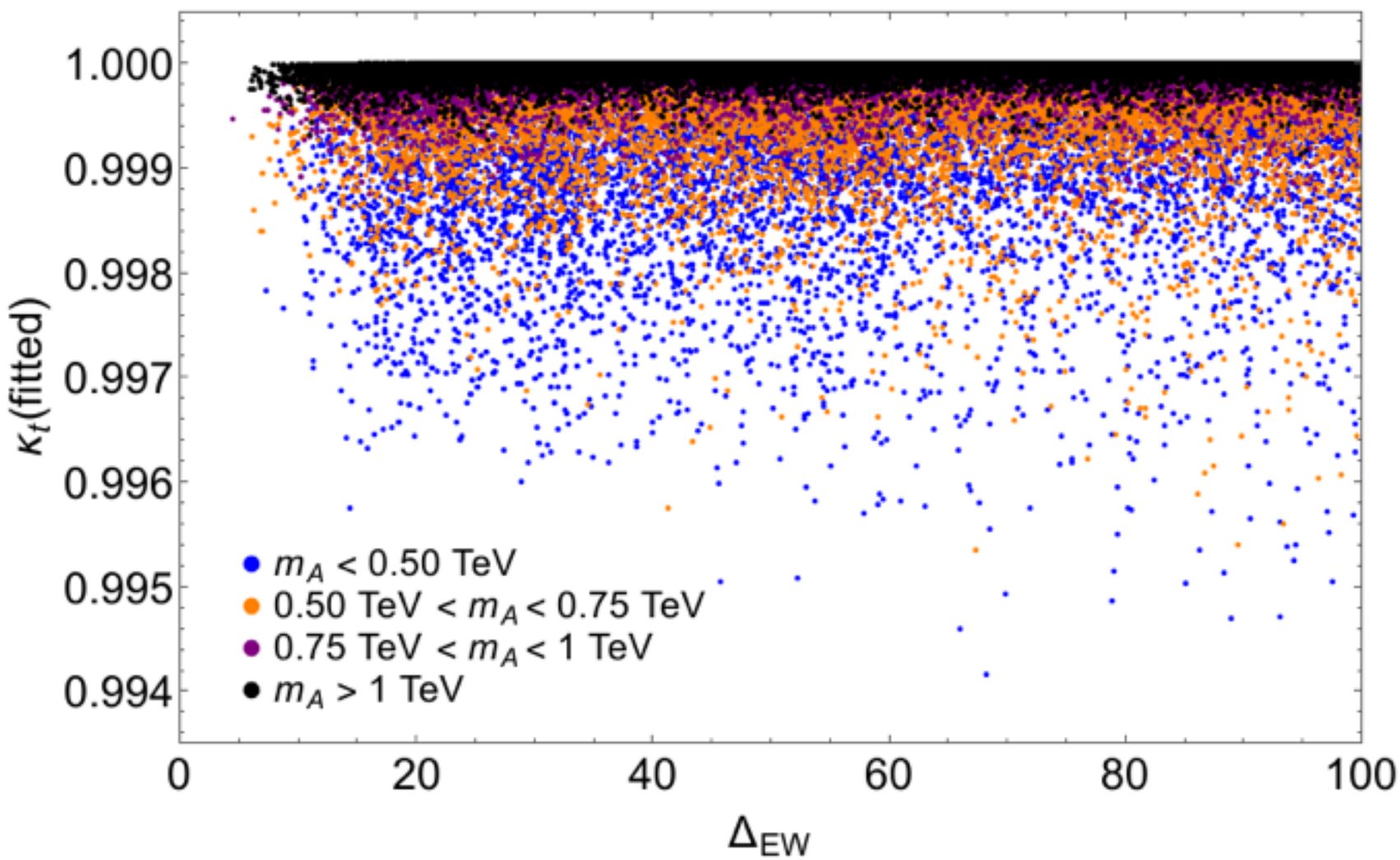


- large value for heavy stop; anti-correlation with fine-tuning measure
- can be seen if B/tau precision measurements are conducted

H-F-F COUPLINGS (3)

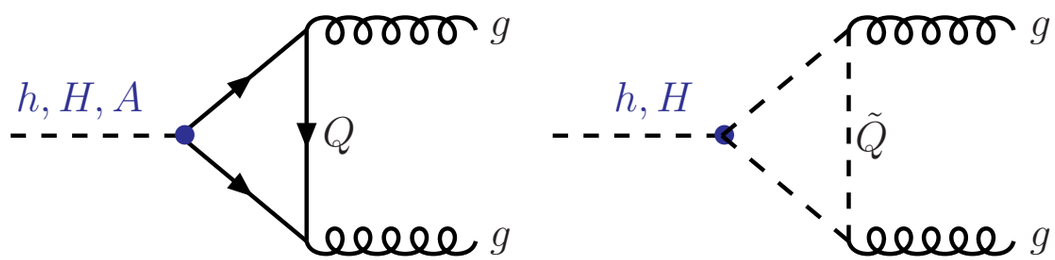
Higgs-top coupling: no significant deviation

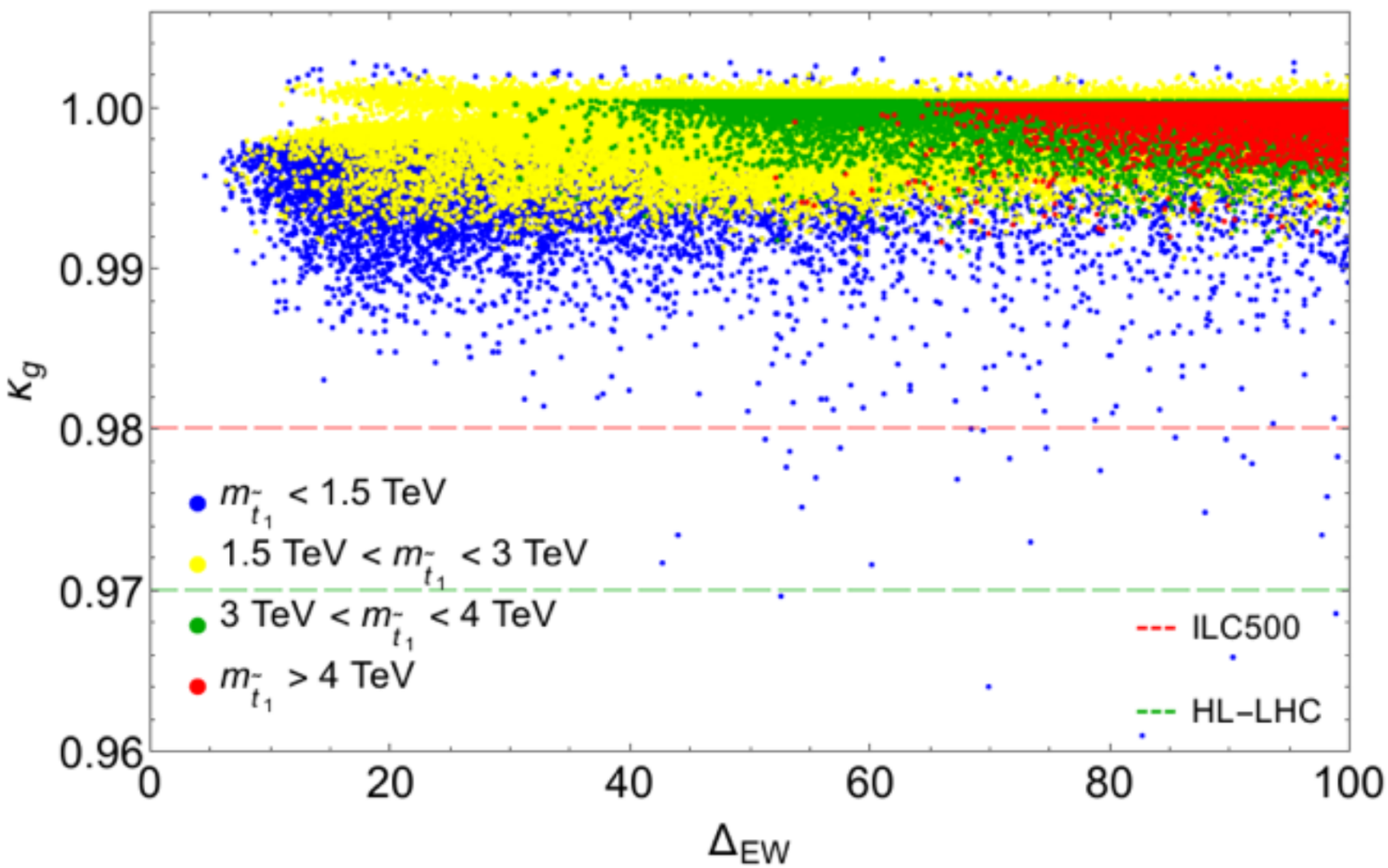
$$g_{htt} = g_{htt}^{\rm SM}\left[\sin(\alpha+\beta)+\frac{\cos(\alpha+\beta)}{1+\Delta_t}\left\{(1+\Delta_t)\cot\beta-(1+\cot^2\beta)\frac{\Delta f_t}{f_t}\right\}\right]$$



H-G-G COUPLINGS

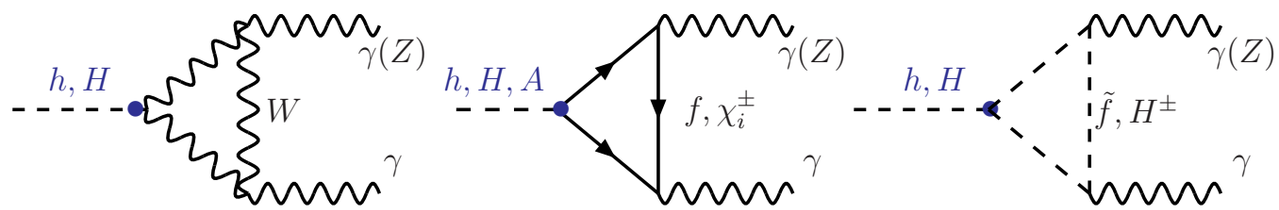
Loop-induced couplings



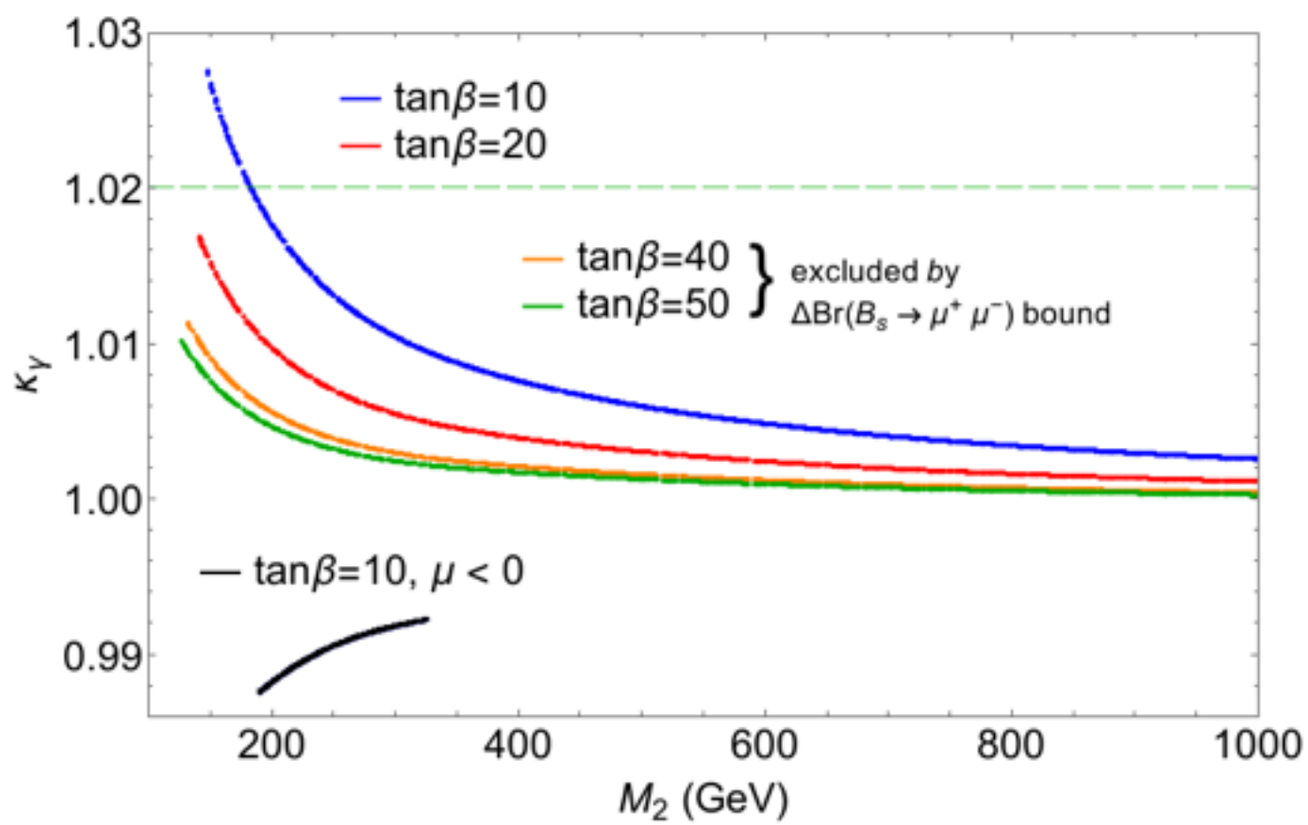


H-Γ-Γ COUPLINGS

Loop-induced couplings



- *If Higgsino-Wino mixing is large, chargino contribution can make a large deviation.*



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LIGHT HIGGSINOS (1)

EWSB condition: $m_Z^2/2 \simeq -\mu^2 - m_{H_u}^2$

*"**Natural**" EWSB requires* $\mu^2 \sim m_{H_u}^2 \sim m_Z^2 \ll m_{\rm soft}^2 \sim \mathcal{O}(\mathrm{TeV}^2)$

Bino > 300 GeV
Wino > 600 GeV

if

gaugino masses are unified at $m_{\rm GUT}$
gluino mass > 1.8 TeV

Higgsino-like neutralinos/chargino $\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_1^\pm$

- nearly degenerate near 100 GeV
- soft leptons(jets) in $\tilde{\chi}_1^+\tilde{\chi}_1^- \to l\nu\tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0$
  $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^- \tilde{\chi}_1^0$
- *difficult to detect at LHC, but good at ILC*

LIGHT HIGGSINOS (2)

Neutralino mass

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0. \end{pmatrix} \longrightarrow \boxed{\begin{aligned} m_{\tilde{\chi}_1^0} &\simeq \mu - \frac{M_Z^2 s_W^2 (1+s_{2\beta})}{2(M_1-\mu)} - \frac{M_Z^2 c_W^2 (1+s_{2\beta})}{2(M_2-\mu)} \\ m_{\tilde{\chi}_2^0} &\simeq \mu + \frac{M_Z^2 s_W^2 (1-s_{2\beta})}{2(M_1-\mu)} + \frac{M_Z^2 c_W^2 (1-s_{2\beta})}{2(M_2-\mu)} \end{aligned}}$$

Chargino mass

$$\begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix} \longrightarrow \boxed{m_{\tilde{\chi}_1^\pm} \simeq \mu - \frac{m_W^2}{M_2} s_{2\beta}}$$

- Due to *Bino/Wino contamination*, neutralino/chargino masses are modified from mu by $\mathcal{O}\left(m_Z^2/M_{1,2}\right)$
- *from precision mass measurements of Higgsino-like states, we can also see the effects of Bino & Wino*

GAUGINO MASS

RG running

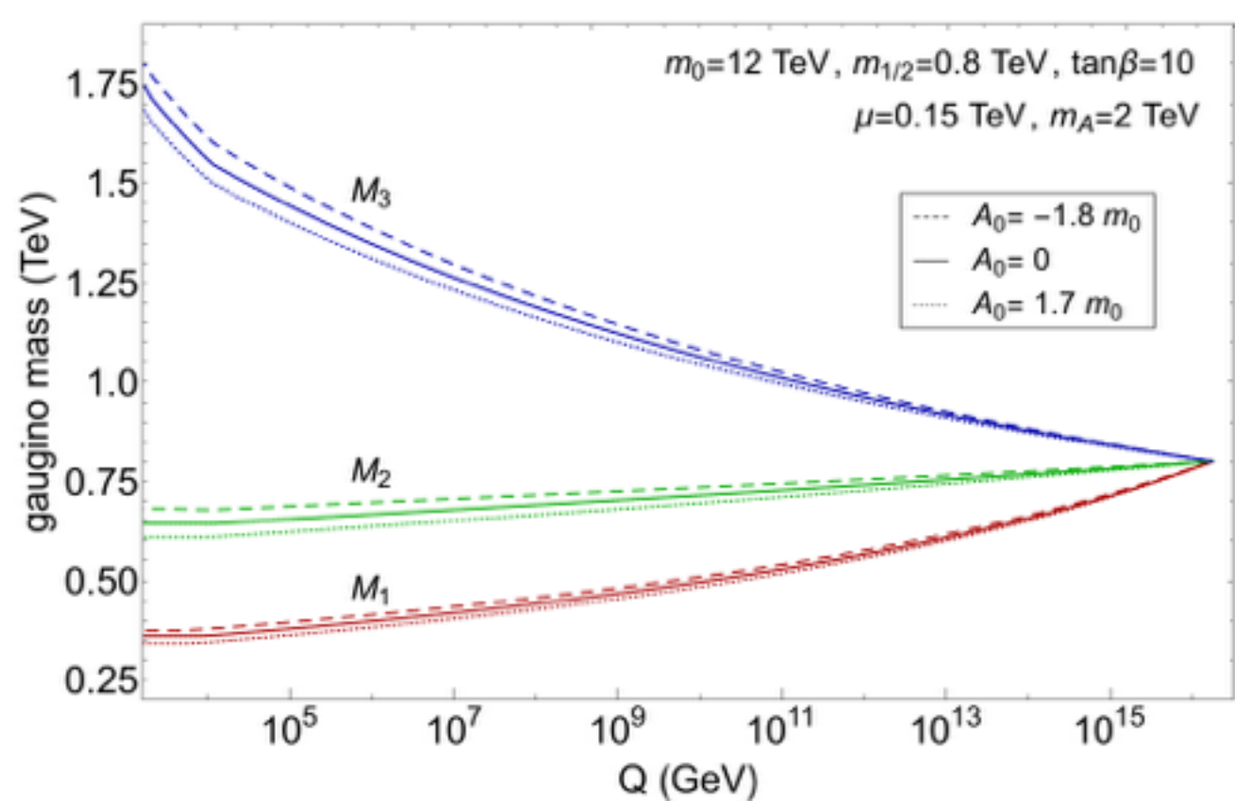
$$\frac{dM_1}{dt} = \frac{2}{16\pi^2}\frac{33}{5}g_1^2 M_1 + \frac{2g_1^2}{(16\pi^2)^2}\left[\frac{199}{25}g_1^2(2M_1) + \frac{27}{5}g_2^2(M_1+M_2) + \frac{88}{5}g_3^2(M_1+M_3) + \frac{26}{5}f_t^2(A_t - M_1) + \frac{14}{5}f_b^2(A_b - M_1) + \frac{18}{5}f_\tau^2(A_\tau - M_1)\right],$$

$$\frac{dM_2}{dt} = \frac{2}{16\pi^2}g_2^2 M_2 + \frac{2g_2^2}{(16\pi^2)^2}\left[\frac{9}{5}g_1^2(M_2+M_1) + 25g_2^2(2M_2) + 24g_3^2(M_2+M_3) + 6f_t^2(A_t - M_2) + 6f_b^2(A_b - M_2) + 2f_\tau^2(A_\tau - M_2)\right],$$

$$\frac{dM_3}{dt} = \frac{2}{16\pi^2}(-3)g_3^2 M_3 + \frac{2g_3^2}{(16\pi^2)^2}\left[\frac{11}{5}g_1^2(M_3+M_1) + 9g_2^2(M_3+M_2) + 14g_3^2(2M_3) + 4f_t^2(A_t - M_3) + 4f_b^2(A_b - M_3)\right],$$

A-terms contribute at 2-loop

Can we extract the A-term contribution from Higgsino mass measurements?

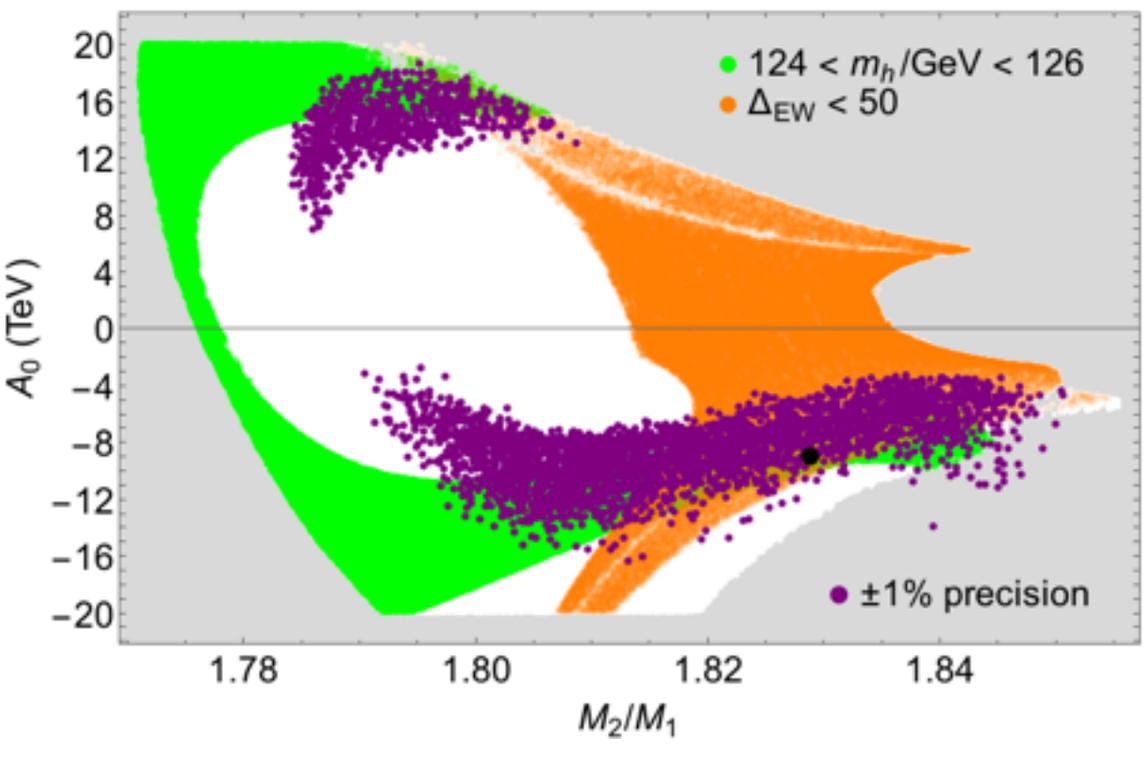


HOW PRECISE?

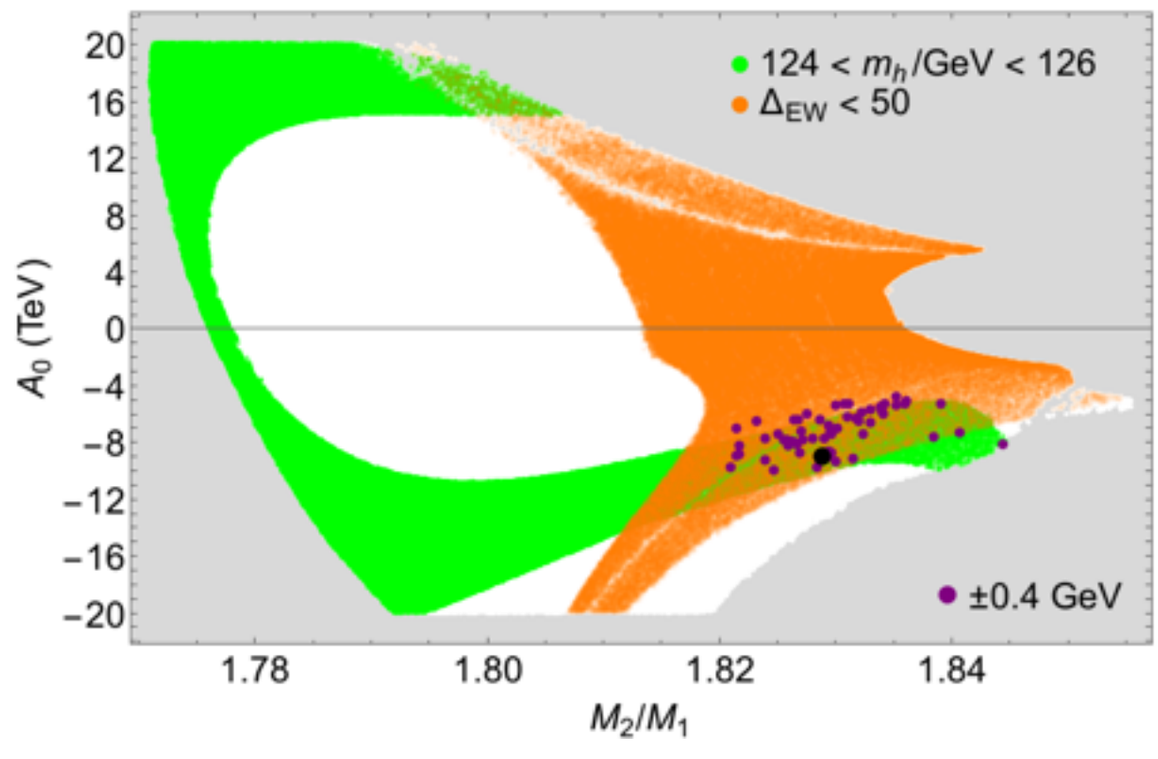
Benchmark study, e. g. $\mu = 150\ \mathrm{GeV}$ with precision requirements

- event cross section with 3% accuracy $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to l\nu\tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0$ $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+l^-\tilde{\chi}_1^0$
- Higgs mass ±1 GeV
- Higgs coupling (at the level of HL-LHC / ILC)
- neutralino/chargino mass

1% precision



±0.4 GeV precision



- 1% is not enough to extract A-term, but 0.4 GeV (sub-percent level) can do.

SUMMARY

- Hope for SUSY discovery at LHC now becomes dim.
- We could still see the SUSY signal from precision measurements of Higgs couplings at LHC and ILC.
- Light Higgsinos are still allowed and good for naturalness. It may be possible to detect them at ILC
- If we discover Higgsino-like states at ILC, we can extract the information of heavy states from precision measurements of Higgsinos