Enhancement of the “CP-odd” Higgs Boson Production in the MSSM with Explicit CP Violation

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II. $\sigma(gg \longrightarrow A^0)$ in the CP violating MSSM
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In collab. with **Q.-H. Cao, K. Tobe** and **C.-P. Yuan**.

Higgs Sector in the MSSM — Introduction

The MSSM has 2 Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}.$$

8 real d.o.f., 3 of which are eaten by $W^\pm$ and Z.

After the EW symmetry breaking, we are left with 5 d.o.f.,

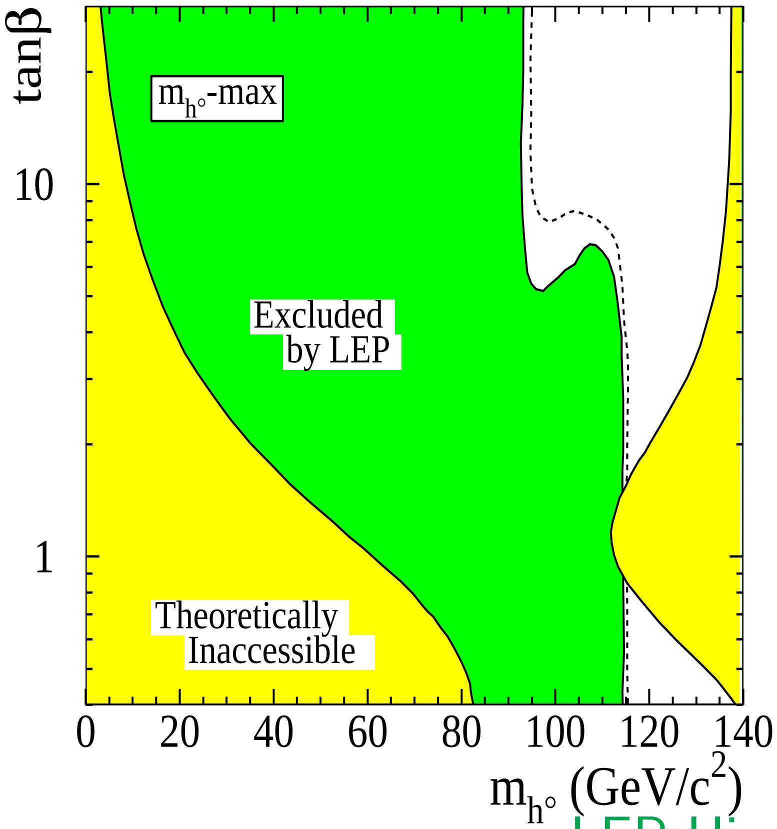
h^0, H^0	CP-even Higgs bosons
A^0	CP-odd Higgs boson
$H^\pm$	charged Higgs bosons

If CP is not a good symmetry, h^0, H^0 and A^0 can mix with each other.

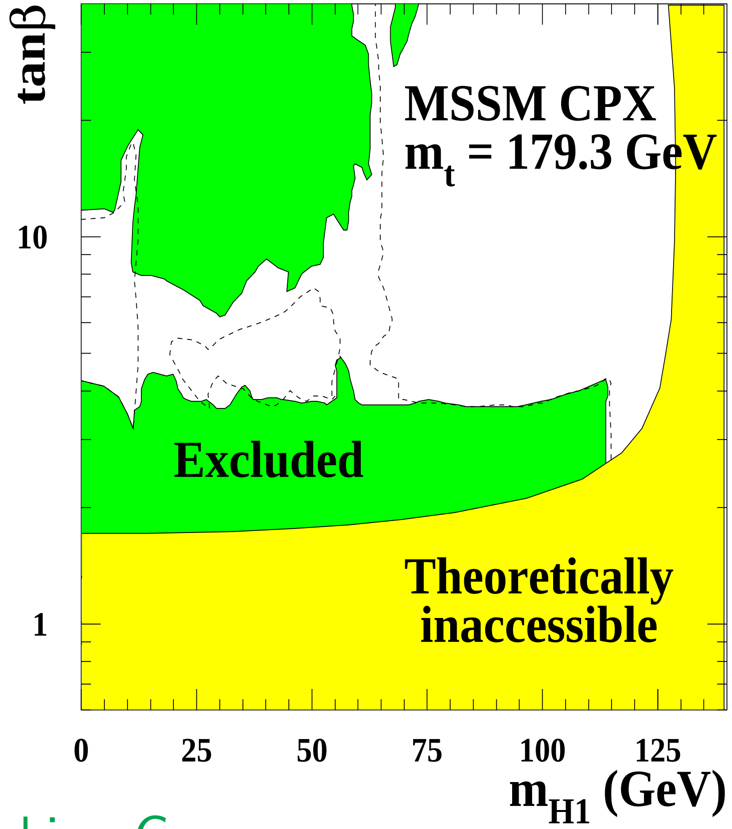
In this talk I concentrate on $\boldsymbol{gg \to A^0}$.

Motivation for the CP violating Higgs Sector

CP conserving case:



CP violating case:



LEP Higgs Working Group

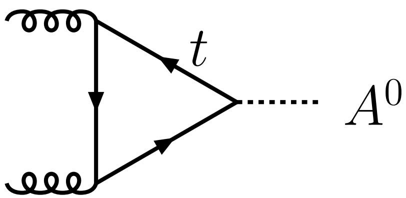
Broader parameter region to be explored for the **CP violating** case

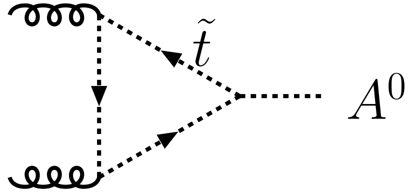
Many works already exist (Carena, Choi, Demir, Drees, Ellis, Gunion, Haber, Hagiwara, Heinemeyer, Hollik, Kalinowski, Kane, Lee, Pilaftsis, Wagner, Wang, Weiglein, Zerwas, . . .)

CP violation and $gg \longrightarrow A^0$

In this talk we concentrate on $\boldsymbol{gg \longrightarrow A^0}$. Why $gg \to A^0$?

CP conserving contrib.: $\boldsymbol{A^0 G^{\mu\nu} \widetilde{G}_{\mu\nu}}$ **CP violating** contrib.: $\boldsymbol{A^0 G^{\mu\nu} G_{\mu\nu}}$





(★ Sources of CP violation: the A term and the LR mixing of stop)

The total cross section is the sum of the squares (no interference terms).

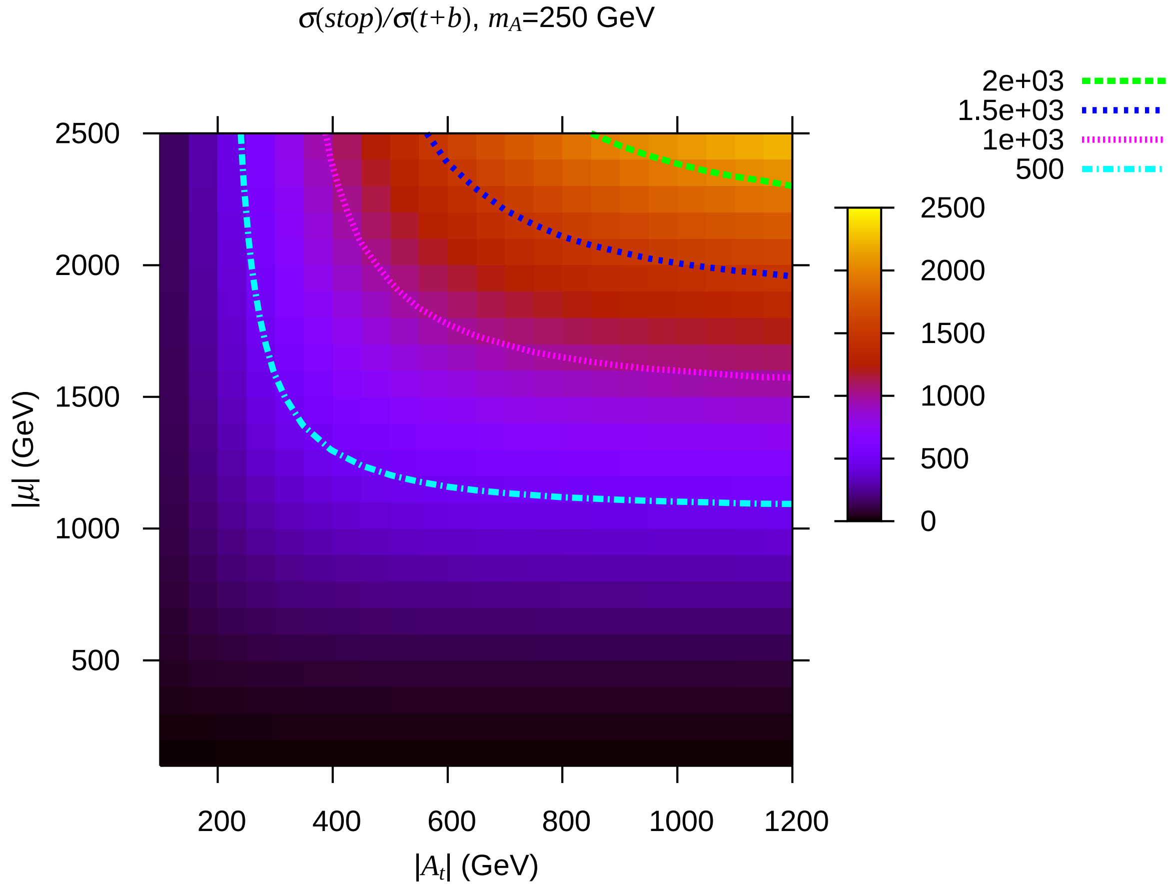
$$\boxed{\boldsymbol{\sigma(gg \longrightarrow A^0) \propto \left(|\mathcal{M}(\mathrm{top})|^2 + |\mathcal{M}(\mathrm{stop})|^2 \right)}} \, .$$

We **ALWAYS gain** (if we neglect the CP-violating mixing among Higgs bosons).

(**cf** For $gg \longrightarrow h^0$, both top and stop diagrams contribute to $\boldsymbol{h^0 G^{\mu\nu} G_{\mu\nu}}$. The interference is typically **destructive** (Choi-Hagiwara-Lee).)

Numerical Results for

$\sigma(gg \to A^0; \tilde{t}\text{-loop})/\sigma(gg \to A^0; t \text{ or } b\text{-loop})$



MSSM
stop mixing: maximal
A_t: pure imaginary
μ: real and positive
$\tan\beta$=5
$m_{\tilde{t}_1} = 120$ GeV
$m_A = 250$ GeV

An $\mathcal{O}(1000)$ enhancement possible, if we neglect (indirect) EDM constraints.

Why such a huge enhancement?

For a pure imaginary A_t, a real μ and maximally mixed stops,

$$\begin{aligned}\sigma(gg \to A; \tilde{t}\text{-loop}) = c\frac{m_t^2}{m_A^2}\frac{\mu^2|A_t|^2}{m_A^2(|A_t|^2 + \mu^2\cot^2\beta)}&|m_{\tilde{t}_1}^2 C_0(m_{\tilde{t}_1}^2, m_A^2)\\ &- m_{\tilde{t}_2}^2 C_0(m_{\tilde{t}_2}^2, m_A^2)|^2,\end{aligned}$$

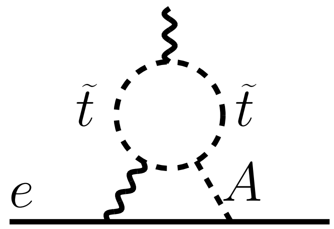
$$\sigma(gg \to A; t\text{-loop}) = c\frac{1}{\tan^2\beta}|m_t^2 C_0(m_t^2, m_A^2)|^2.$$

For $|A_t| \sim 1$TeV, $\mu \sim 2$TeV, $m_A = 250$GeV and $\tan\beta = 5$ the ratio of the red parts is $\mathcal{O}(1000)$. (**Large A_t and/or μ** and the **$\tan\beta$ dependence**.)

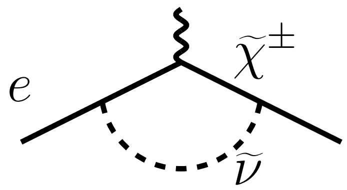
The behavior of the C_0 function is also important. If $m_A < 2m_{\tilde{t}_1}$, then $|\cdots| = |(\text{real}) - (\text{real})|$, where a GIM-like cancellation happens. If $2m_{\tilde{t}_1} < m_A < 2m_{\tilde{t}_2}$, then $|\cdots| = |(\text{complex}) - (\text{real})|$, where the cancellation tends to be less severe.

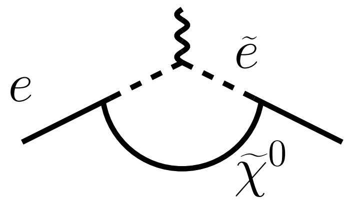
Constraints from EDM

Potentially strong constraint comes from electron/neutron EDM from the Barr-Zee diagrams, (Chang-Keung-Pilaftsis, . . .)



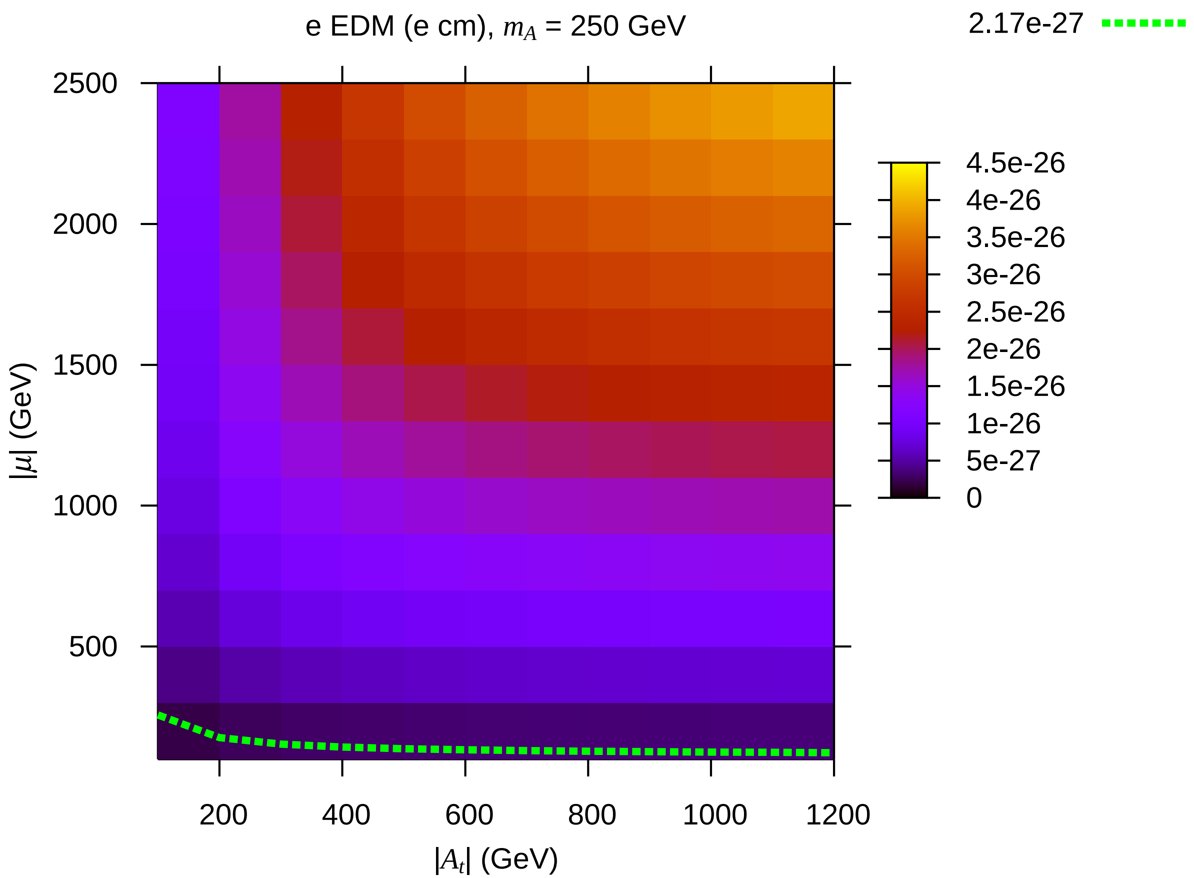
If this exceeds the exp. bound, to make the parameter region viable, we need a cancellation from other contributions, e.g.





by fine-tuning the phase of gaugino mass parameters, etc.

Constraints from EDM, Numerical Results

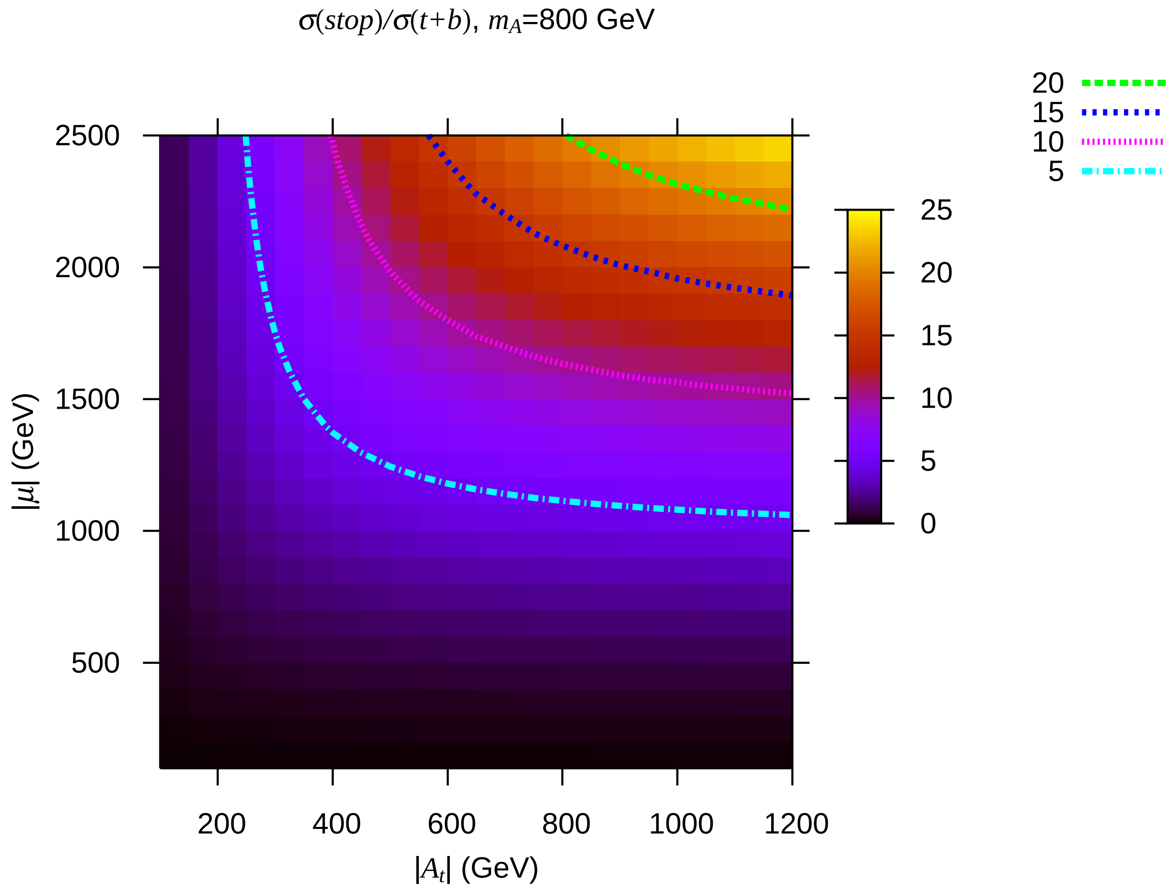


Electron EDM

Includes the 2-loop contributions (Barr-Zee diagrams) only

Typically, the 2-loop contribution exceeds the exp. bound by a factor of $\mathcal{O}(10)$ in the parameter region shown. To make this parameter region viable, we need a cancellation from other contrib., e.g. 1-loop contributions.

Another Numerical Result for $\sigma(gg \to A^0; \tilde{t}\text{-loop})/\sigma(gg \to A^0; t \text{ or } b\text{-loop})$ in a different, EDM-safe parameter region



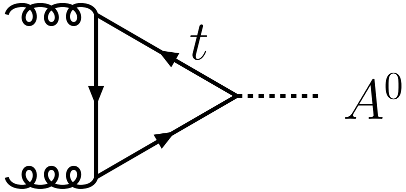
MSSM
stop mixing: maximal
A_t: pure imaginary
μ: real and positive
$\tan\beta = 5$
$m_{\tilde{t}_1} = 390$GeV (heavier than the prev. case)
$m_A = 800$GeV (heavier than the prev. case)

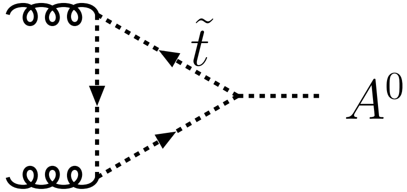
Most of the region in the fig. is safe from EDM.

An $\mathcal{O}(10)$ enhancement possible

Connection to ILC

How do we distinguish **which operator** is important,
CP conserving operator $A^0 G^{\mu\nu} \widetilde{G}_{\mu\nu}$ or **CP violating** operator $A^0 G^{\mu\nu} G_{\mu\nu}$?

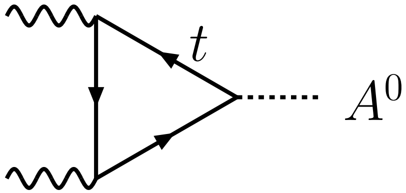


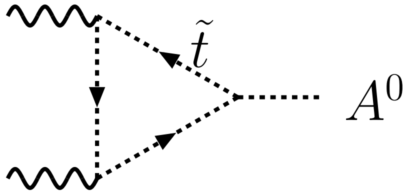


Polarized photon-photon collision at the **ILC** may be useful since the dependence on the polarization vectors is different,

$$\mathcal{M}(\gamma\gamma \to A \text{ from } A F^{\mu\nu} F_{\mu\nu}) \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2$$

$$\mathcal{M}(\gamma\gamma \to A \text{ from } A F^{\mu\nu} \widetilde{F}_{\mu\nu}) \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{k}_1$$





Summary

We calculated $\sigma(gg \to A^0)$ in the MSSM with CP violating A_t term.

✓ We found the parameter region in which the cross section is enhanced by a factor of ~ 1000 from CP-violating stop-loop diagrams. However, this parameter region suffers from too large EDMs from 2-loop diagrams (Barr-Zee diagrams).

▶ To make the parameter region viable, we have to cancel this contribution by other contributions, e.g. 1-loop diagrams.

✓ We also found another parameter region which is safe from the 2-loop contributions to EDM. In this region the cross section is enhanced by a factor of $\mathcal{O}(10)$.

✓ To test this scenario, **polarized photon-photon collision** at the **ILC** may be useful.

★ Connections to the EW baryogenesis?

Backup Slides

Constraint from Charge/Color Breaking Minimum

For the potential

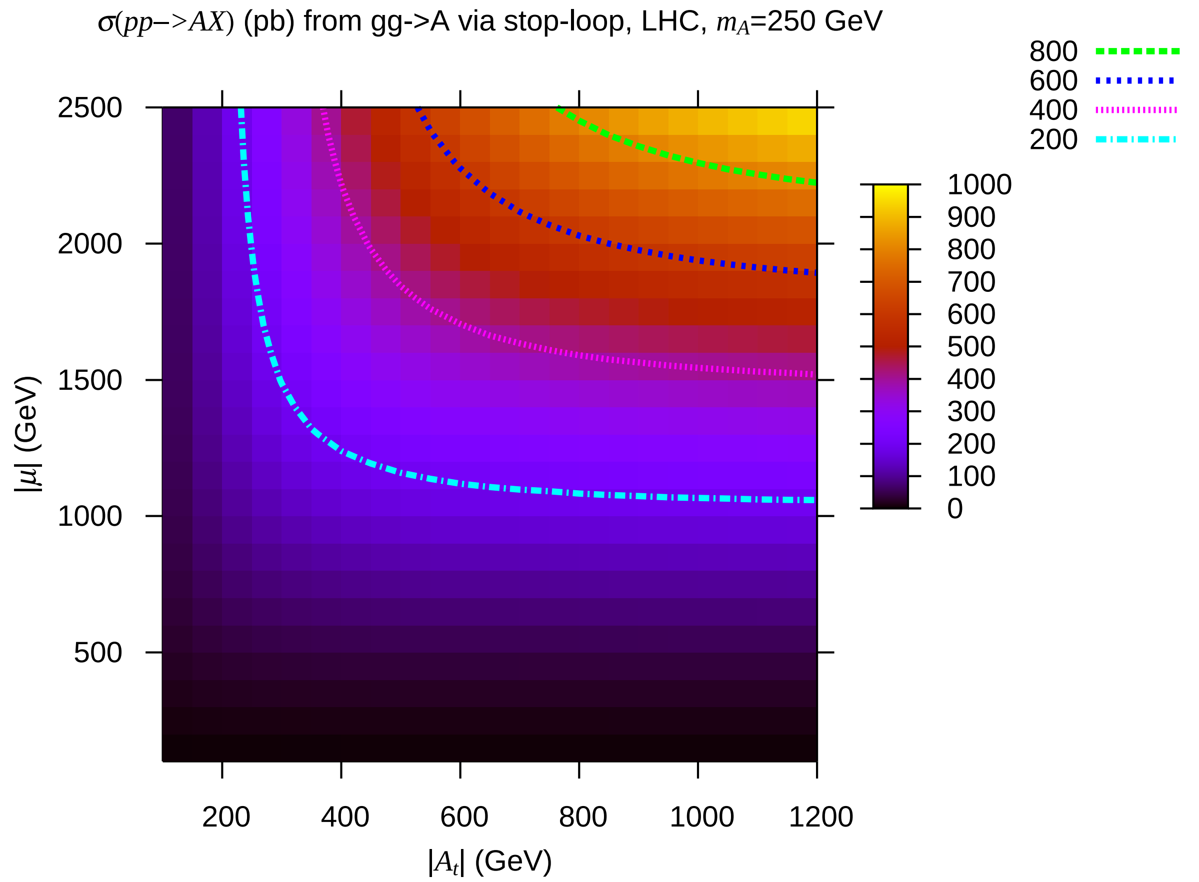
$$V = \sum_{\phi} \left| \frac{\partial W}{\partial \phi} \right|^2 + A(W + W^*) + m_{\mathsf{SUSY}}^2 \sum_{\phi} |\phi|^2,$$

the tree-level condition that the charge/color breaking minimum should not happen is $|A| \leq 3 m_{\mathsf{SUSY}}$ (See, e.g. a review by Nilles). This is actually satisfied for our parameters. (We assumed $m_{\tilde{t}_L}^2 = m_{\tilde{t}_R}^2$ to maximize the mixing and fix $m_{\tilde{t}_1}$ as

$$m_{\tilde{t}_1}^2 = m_{\tilde{t}_{LL}}^2 - |m_{\tilde{t}_{LR}}^2| = \mathcal{O}((100\text{GeV})^2).$$

For $|A_t| \sim |\mu| \sim$ 1TeV, the soft SUSY breaking mass m_{SUSY} is ~ 0.4 TeV.)

Hadronic-level cross section at the LHC



The cross section can be a few times 100 pb.