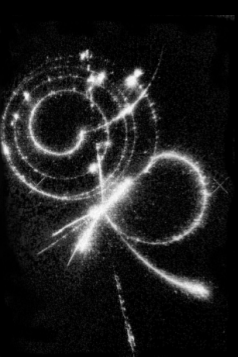
$H_2 \rightarrow H_1 H_1$ decays in the cMSSM

Hunting for the Higgs *in a Complex World*

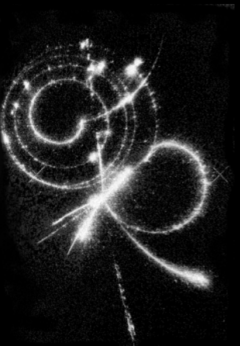


Karina Williams, IPPP, Durham

In collaboration with Georg Weiglein plus others

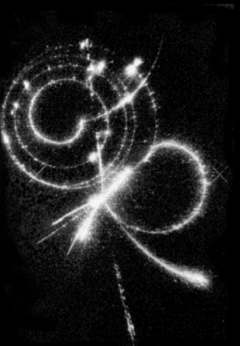
Minimal Supersymmetric Standard Model

- Minimum number of superpartners
- 2 Higgs Doublets
- No assumption about SUSY breaking mechanism - All terms that break SUSY softly are added to Lagrangian
- Has more than 100 free parameters (in addition to those in the SM)
- Predicts that the lightest Higgs Mass < 140 GeV – within reach of the LHC and a LC



complex MSSM (cMSSM)

- Not to be confused with the CMSSM – the Constrained MSSM
- The extra complex phases give rise to CP violation in the Higgs Sector
- A theory with CP violation is needed to describe the matter-antimatter asymmetry in the universe



Stops in the cMSSM

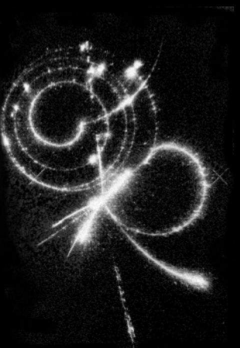
Stop mass mixing matrix can have 2 complex parameters:

$$M_{\tilde{t}} = \begin{pmatrix} M_L^2 + m_t^2 + DT_1 & m_t X_t^* \\ m_t X_t & M_R^2 + m_t^2 + DT_2 \end{pmatrix}$$

$$X_t = A_t - \mu^* \cot\beta$$

Rotate to get physical states:

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \rightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$



The Higgs Potential in the cMSSM

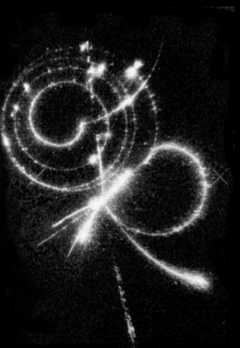
The Higgs potential also has complex parameters:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} + \epsilon_{ij} (m_{12}^2 H_{1i} H_{2j} + m_{12}^{2\,*} H_{1i}^* H_{2j}^*)$$
$$+ \frac{1}{8}(g_1^2 + g_2^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g_2^2 |H_{1i}^* H_{2i}|^2 .$$

One of the Higgs doublets has a complex phase:

$$\mathcal{H}_1 = \begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix},$$

$$\mathcal{H}_2 = \begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$



Lowest Order

Rotate to physical states h, H, A, G
Lowest order has no CP violation

$$\begin{pmatrix} h \\ H \\ A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 & 0 \\ 0 & 0 & -\sin\beta_{\mathrm{n}} & \cos\beta_{\mathrm{n}} \\ 0 & 0 & \cos\beta_{\mathrm{n}} & \sin\beta_{\mathrm{n}} \end{pmatrix} \cdot \begin{pmatrix} \phi_1 \\ \phi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix}$$

Lowest Order

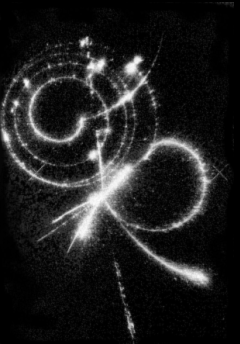
Rotate to physical states h, H, A, G

Lowest order has no CP violation

CP even

$$\begin{pmatrix} h \\ H \\ A \\ G \end{pmatrix} = \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 & 0 \\ 0 & 0 & -\sin\beta_{\mathrm{n}} & \cos\beta_{\mathrm{n}} \\ 0 & 0 & \cos\beta_{\mathrm{n}} & \sin\beta_{\mathrm{n}} \end{pmatrix} \cdot \begin{pmatrix} \phi_1 \\ \phi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix}$$

CP odd



Including loop corrections

Rotate to physical states H_1, H_2, H_3

Mixed CP

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \mathbf{U}_{\mathrm{n}} \cdot \begin{pmatrix} h \\ H \\ A \end{pmatrix}$$

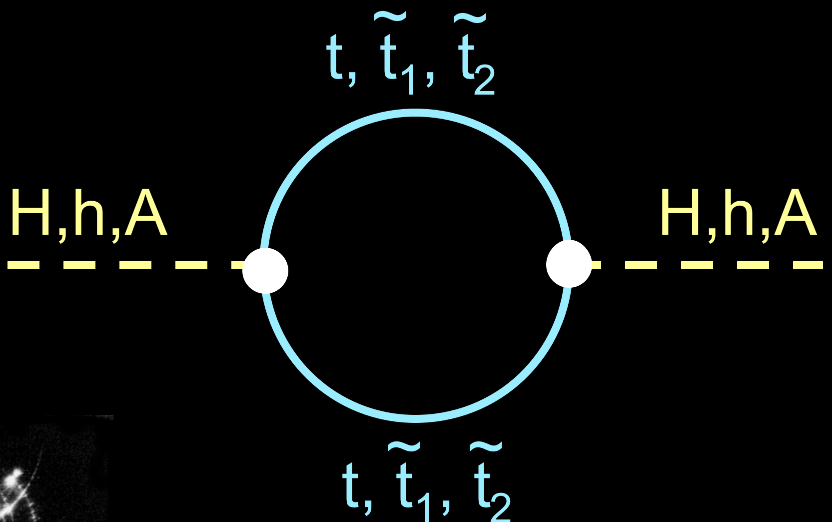
where U_{n} diagonalises the mass matrix:

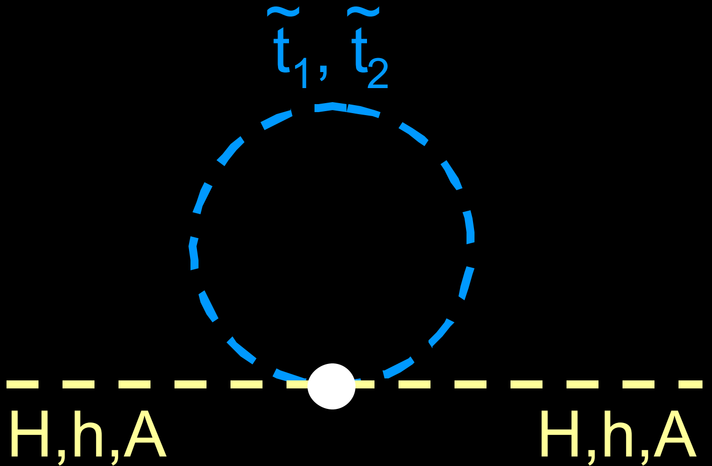
$$\begin{pmatrix} m^2_{h(0)} - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m^2_{H(0)} - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m^2_{A(0)} - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

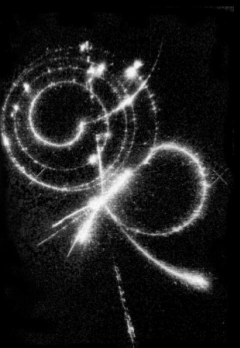
… so need expressions for the renormalised self energies $\hat{S}$

Leading terms for renormalised self-energies:

- top, stop
- one loop
- terms proportional to m_t^4
- $p^2 = 0$







Renormalisation

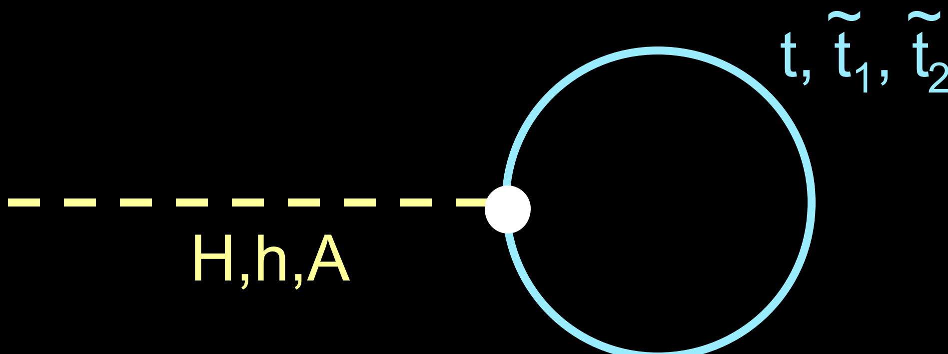
$$\delta T_h = -T_{h(1)}$$

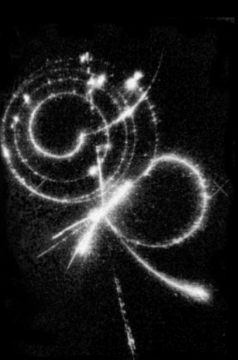
$$\delta T_H = -T_{H(1)}$$

$$\delta T_A = -T_{A(1)}$$

$$\delta m^2_{H^\pm} = \mathrm{Re}\,\Sigma_{H^+H^-}(0)$$

No contribution from δM_Z^2 or $\delta \tan\beta$





2 computer programs…

FeynHiggs

by S. Heinemeyer, T. Hahn, W. Hollik and G.Weiglein

Feynman diagrammatic approach, uses on-shell renormalization scheme

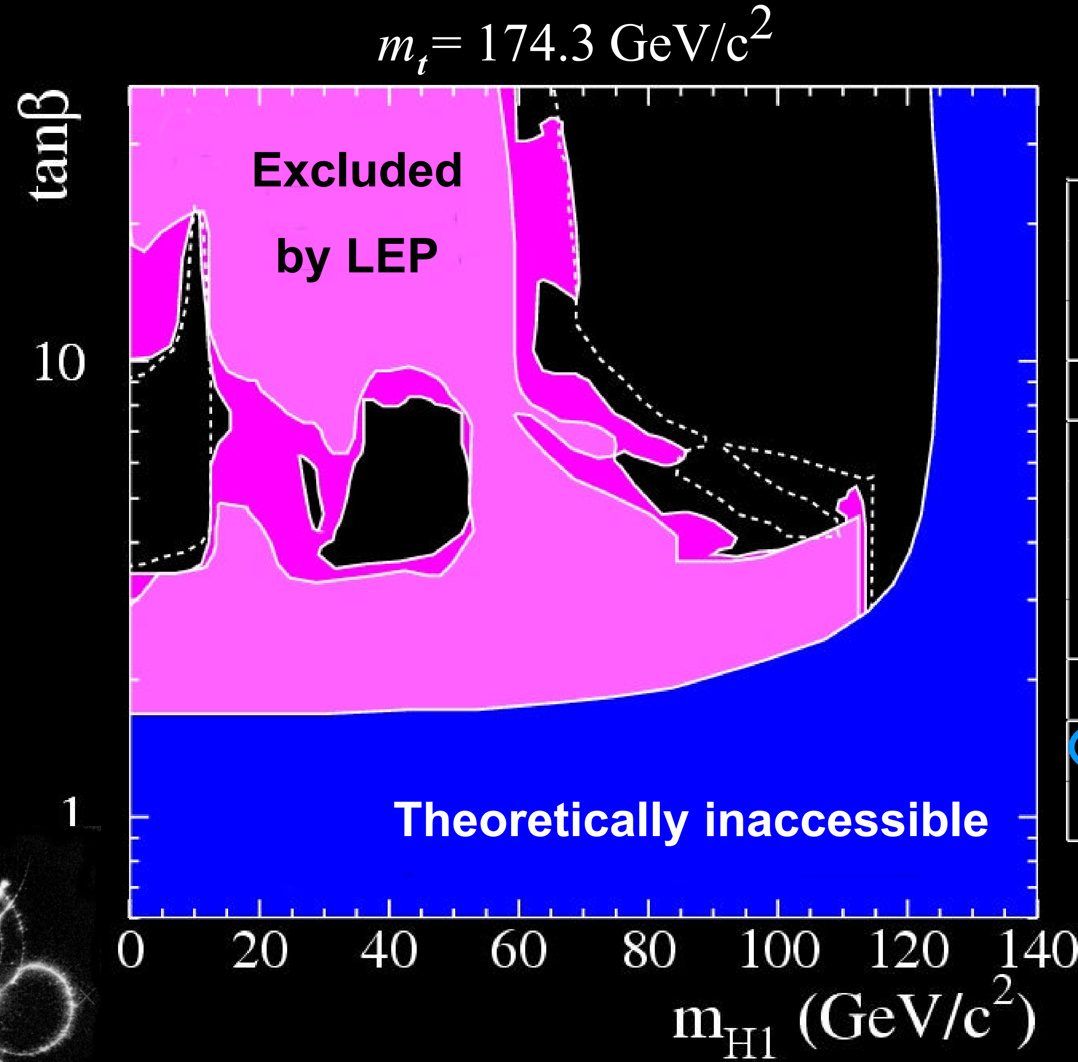
CPsuperH

by Jae Sik Lee, Apostolos Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis and C. E. M .Wagner

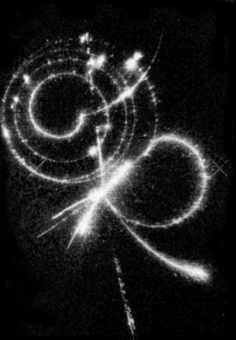
Renormalisation group improved effective potential calculation, uses $\overline{\text{MS}}$ renormalization scheme

…both calculate higgs masses, couplings, branching ratios e.t.c. for cMSSM

LEP results for CPX scenario

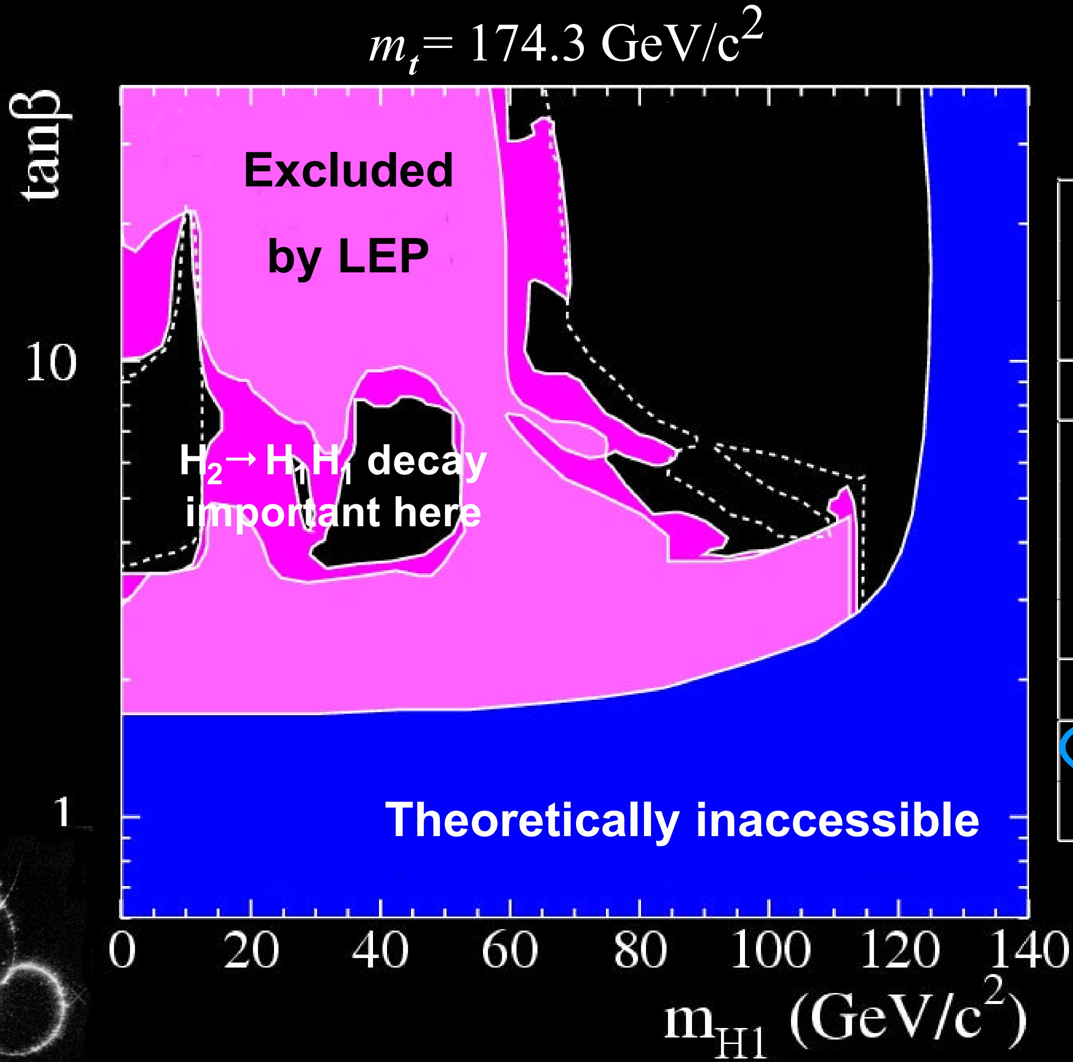


$\tan\beta$	0.6–40
m_A (GeV/c^2)	–
$m_{H^\pm}$ (GeV/c^2)	4–1000
M_{SUSY} (GeV)	500
M_2 (GeV)	200
μ (GeV)	2000
$m_{\tilde{g}}$ (GeV/c^2)	1000
X_t (GeV)	$A - \mu \cot\beta$
A (GeV) $\overline{MS}$	1000
arg A, arg $m_{\tilde{g}}$	90°



From CERN-PH-EP/2006-001

LEP results for CPX scenario



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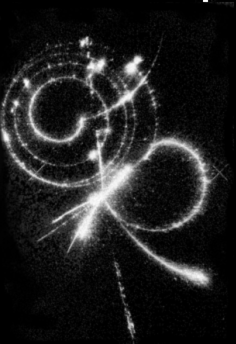
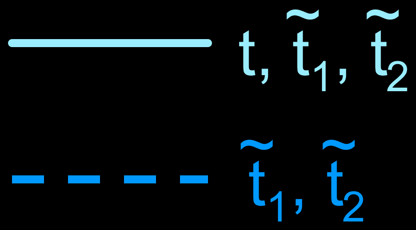
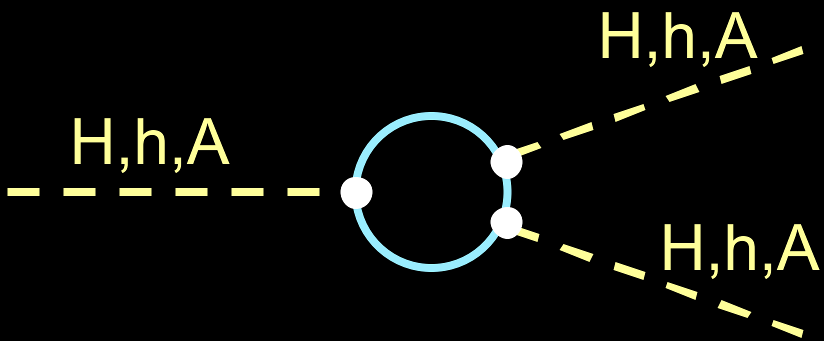


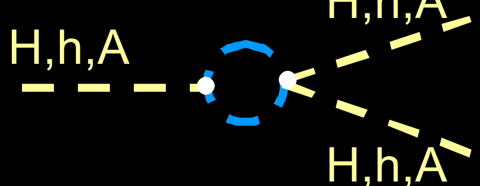
From CERN-PH-EP/2006-001

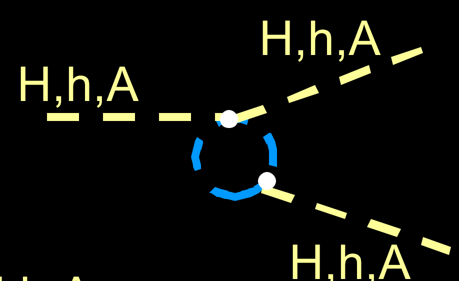


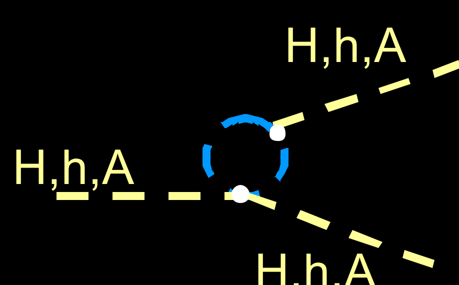
$H_2 \rightarrow H_1 H_1$ vertex corrections

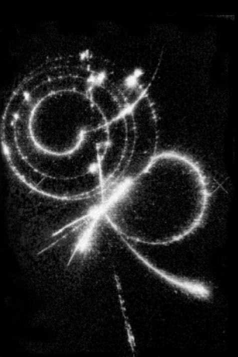


- top, stop
- one loop
- terms proportional to m_t^4
- $p^2 = 0$

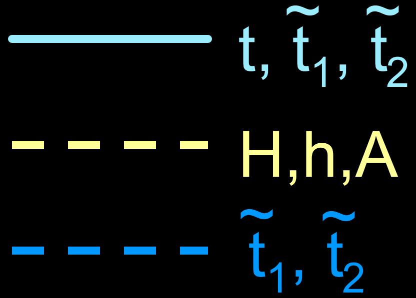




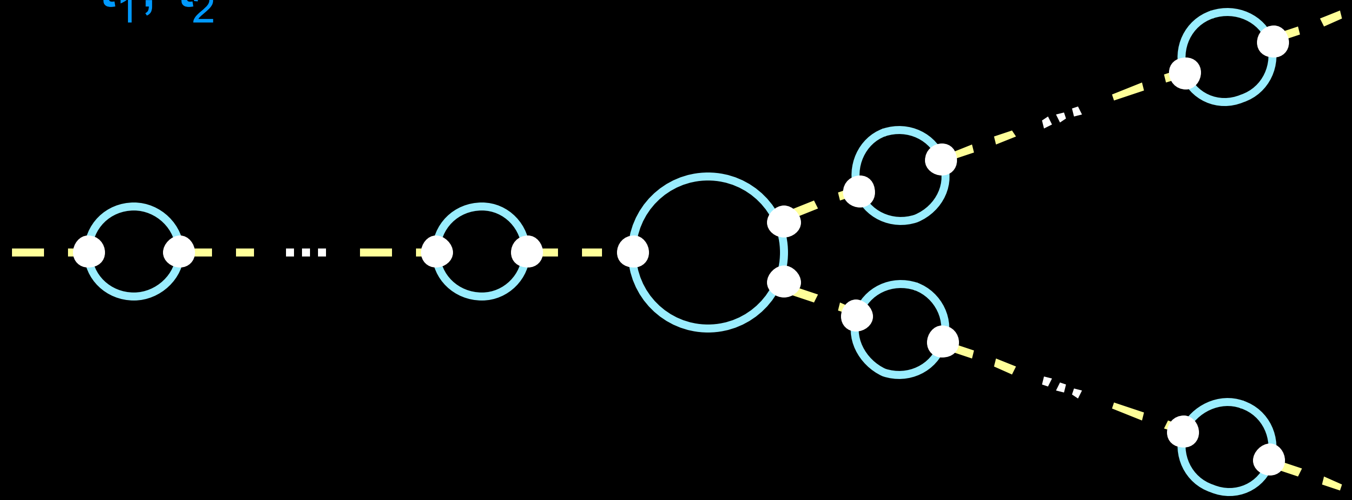


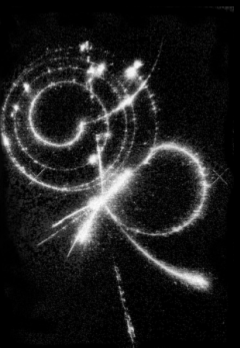


These vertex corrections are finite under these approximations – no counter-terms needed



$H_2 \to H_1 H_1$



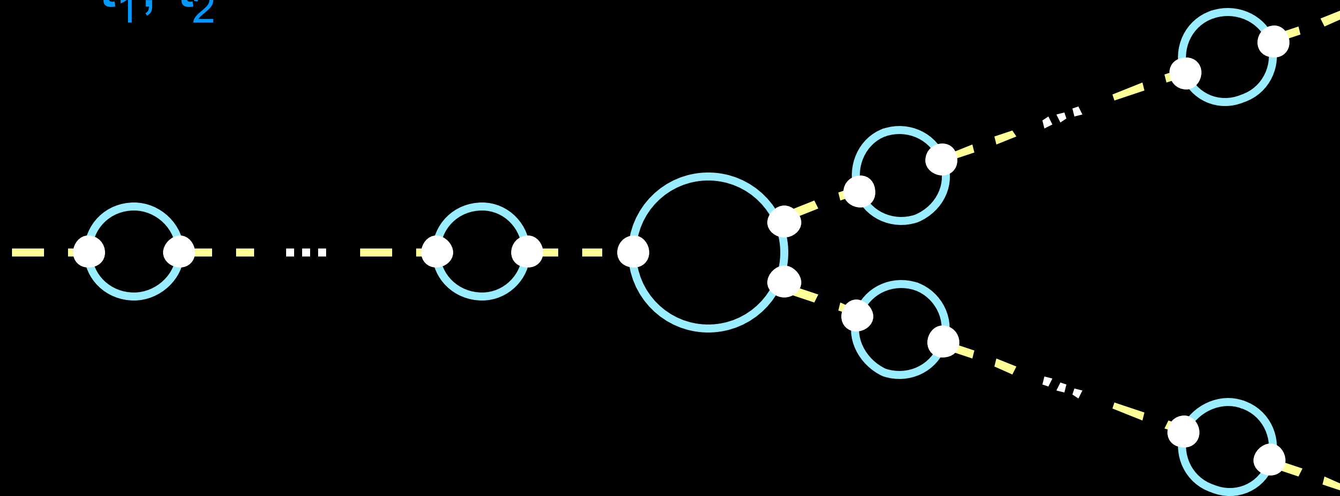


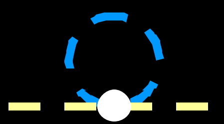
t, $\tilde{t}_1$, $\tilde{t}_2$

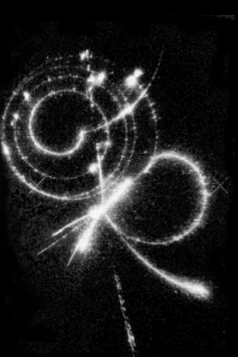
H,h,A

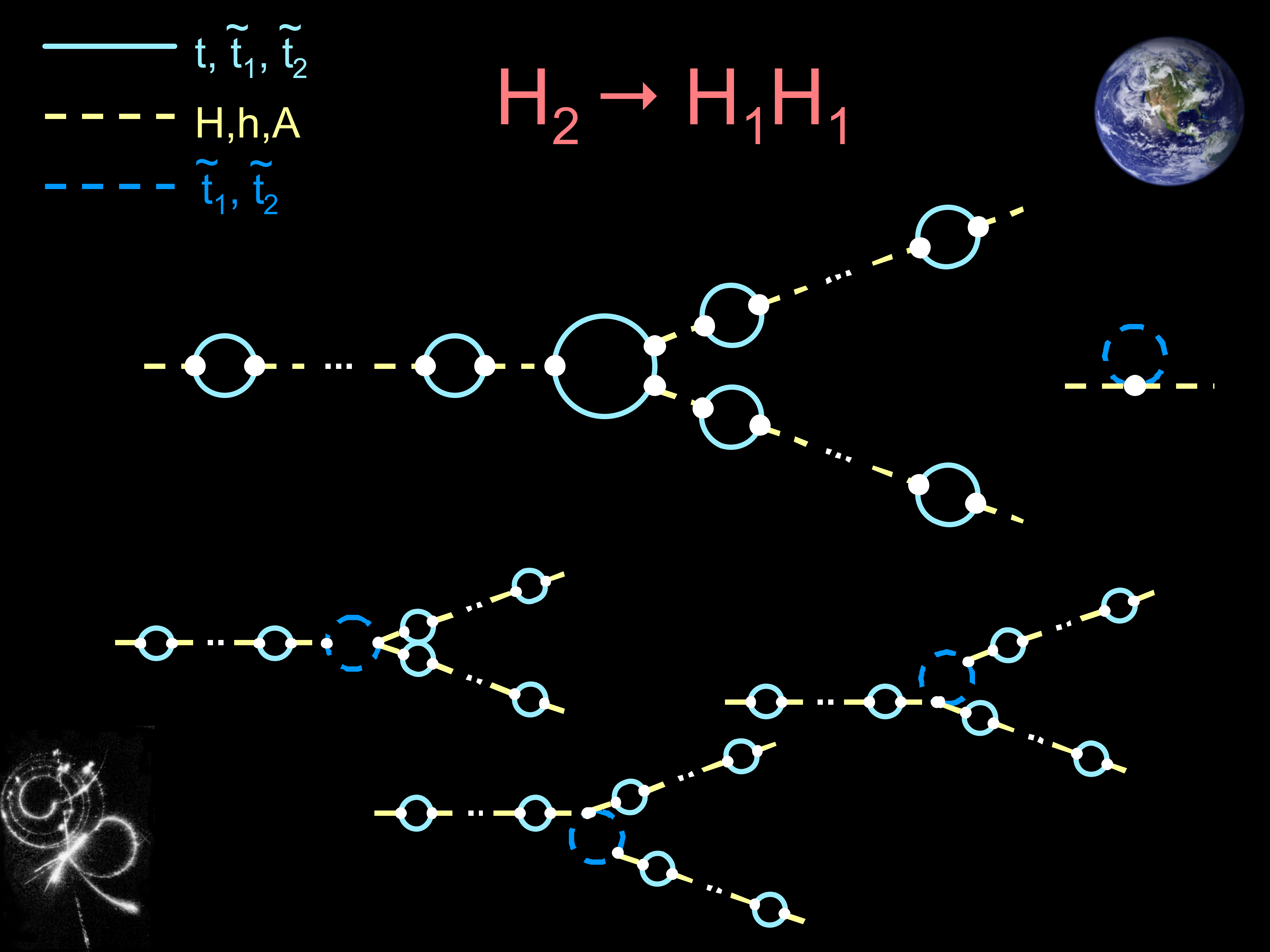
$\tilde{t}_1$, $\tilde{t}_2$

$H_2 \to H_1 H_1$



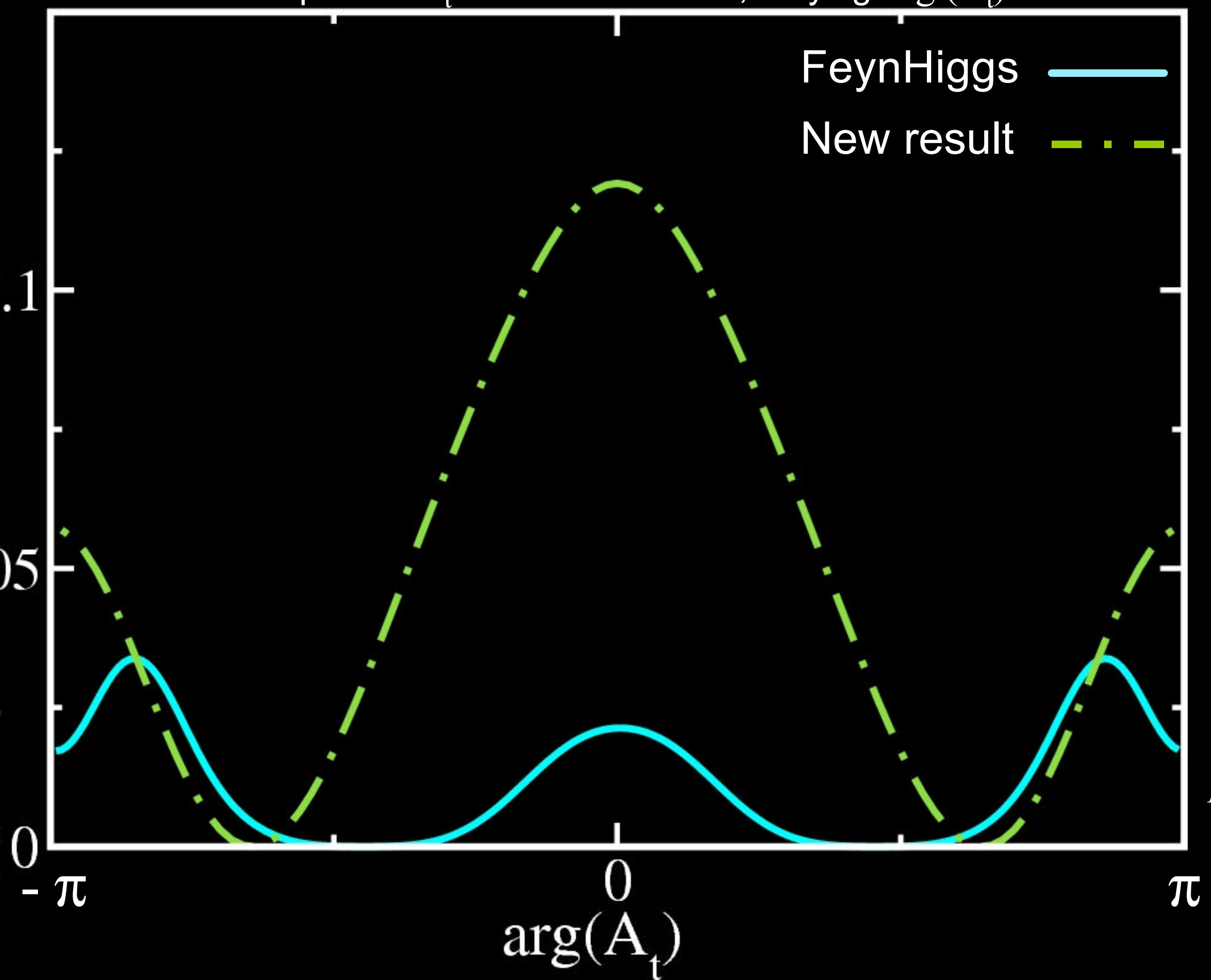





$t, \tilde{t}_1, \tilde{t}_2$
H,h,A
$\tilde{t}_1, \tilde{t}_2$
$H_2 \to H_1 H_1$

$H_2 \rightarrow H_1 H_1$

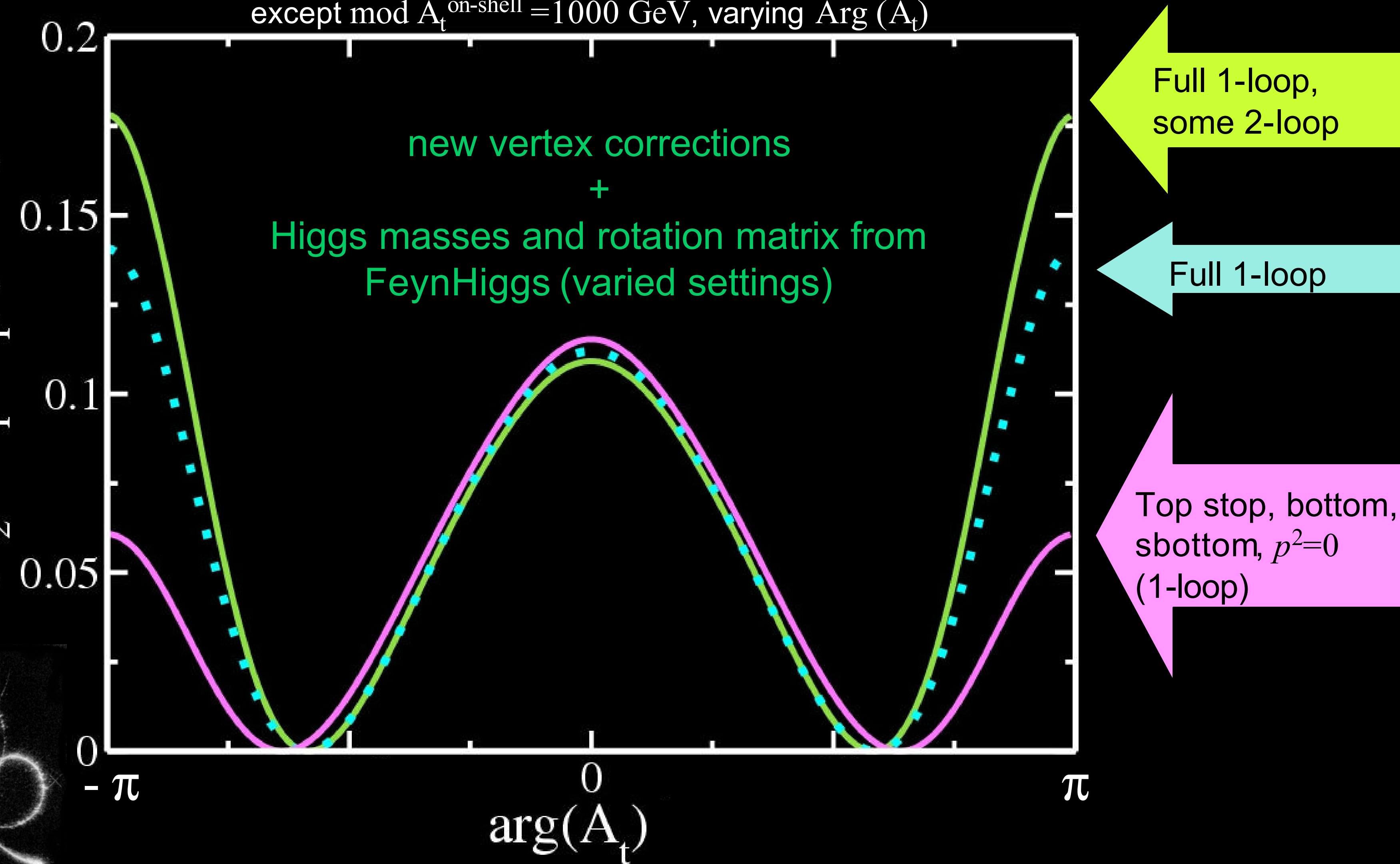
CPX with $\tan\beta = 10$, $M_{H\pm} = 500$ GeV, $m_t = 172.7$ GeV
except mod $A_t^{\text{on-shell}} = 1000$ GeV, varying arg (A_t)

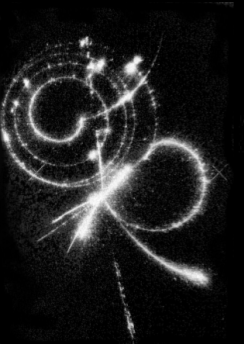


FeynHiggs settings:
top, stop,
bottom, sbottom,
$p^2 = 0$,
1-loop

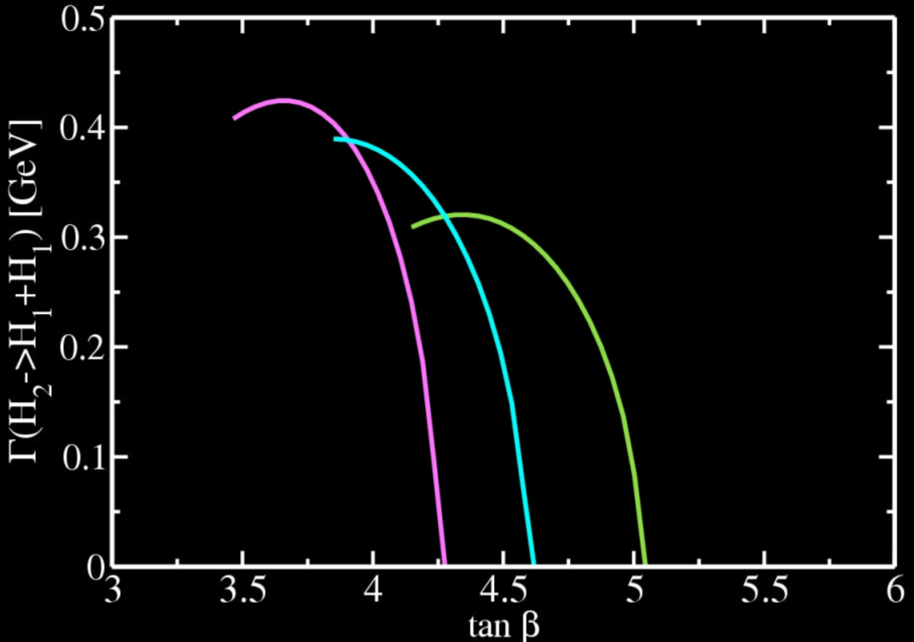
Preview of results

CPX with tanβ =10, $M_{H\pm}$= 500 GeV, m_t =172.7 GeV
except mod $A_t^{on\text{-}shell}$ =1000 GeV, varying Arg (A_t)



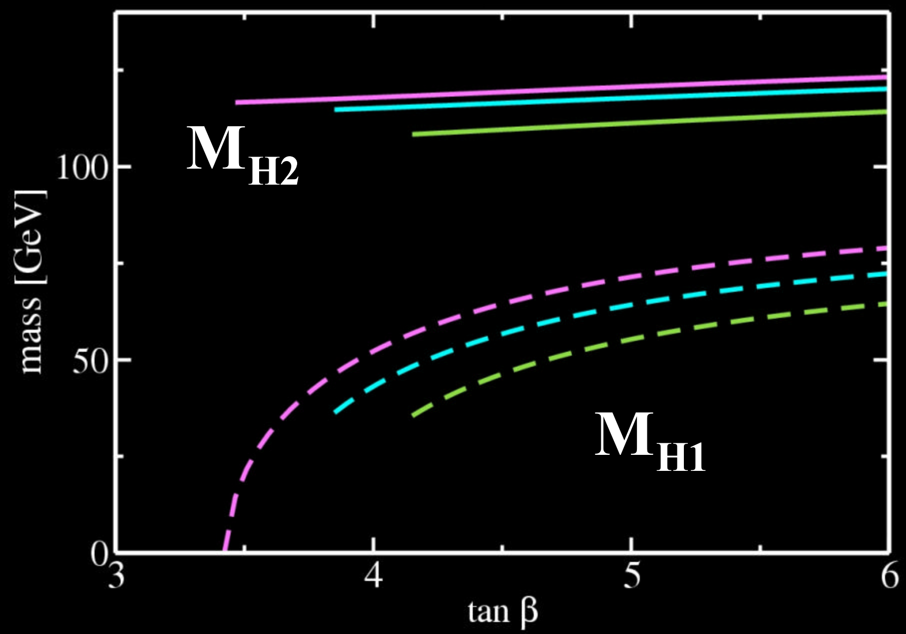


Near the hole in the LEP results…



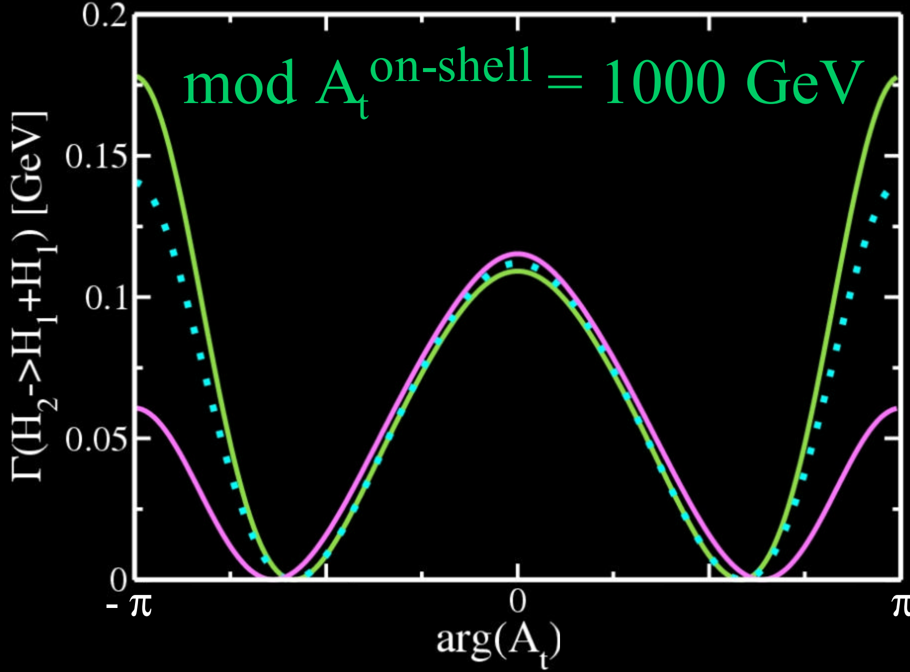
Settings for Higgs masses and rotation matrix from FeynHiggs:

Full 1-loop, some 2-loop
Full 1-loop
Top, stop, bottom, sbottom, $p^2=0$(1-loop)



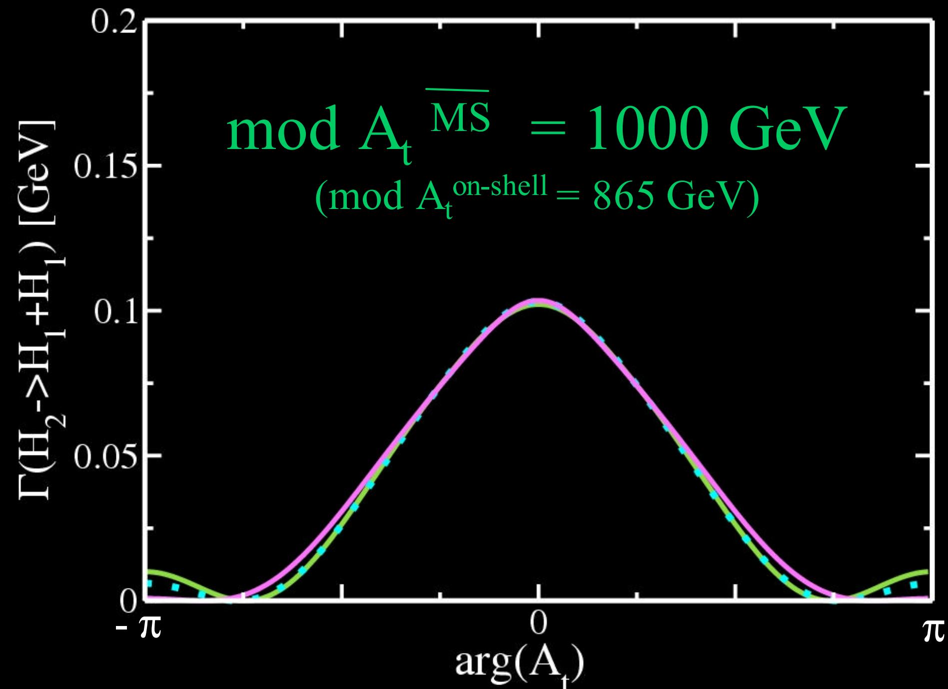
CPX with $M_{H\pm}$= 150 GeV, m_t =172.7 GeV except mod $A_t^{\text{on-shell}}$ =1000 GeV

Changing A_t

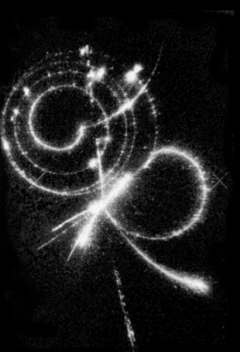


Settings for Higgs masses and rotation matrix from FeynHiggs:

Full 1-loop, some 2-loop	
Full 1-loop	
Top, stop, bottom, sbottom, $p^2=0$(1-loop)	

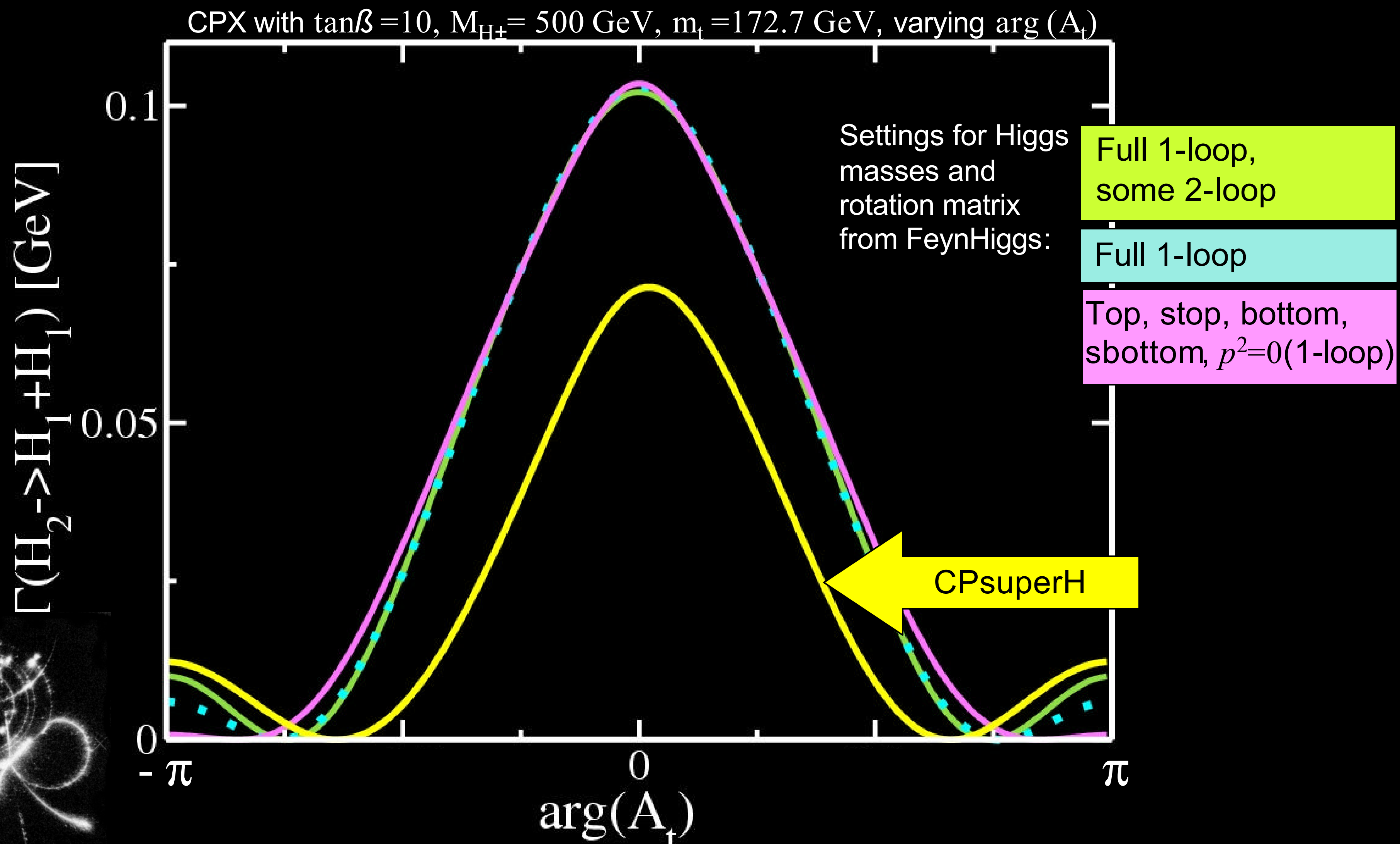


using hep-ph / 0001002
(M. Carena, H.E. Haber, S. Heinemeyer, W. Hollik, C.E.M. Wagner, G. Weiglein)



CPX with $\tan\beta = 10$, $M_{H\pm} = 500$ GeV, $m_t = 172.7$ GeV, varying arg (A_t)

Preview of results and comparison with CPsuperH



Summary

- Improvement to the $H_2 \rightarrow H_1 H_1$ decay width in FeynHiggs

Next…

- full 1-loop vertex corrections
- refine conversion between different definitions of A_t
- comparison with CPsuperH