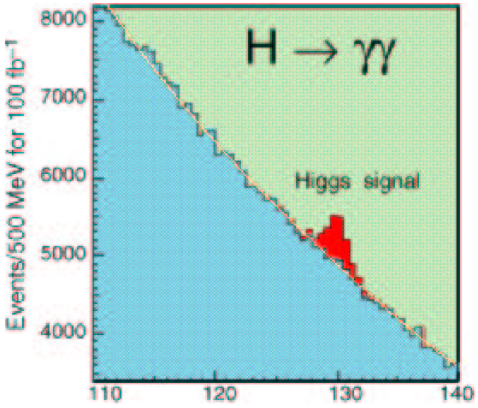
Resonance-Continuum Interference in the LHC $H \to \gamma\gamma$ Signal

Lance Dixon & Stewart Siu (SLAC)



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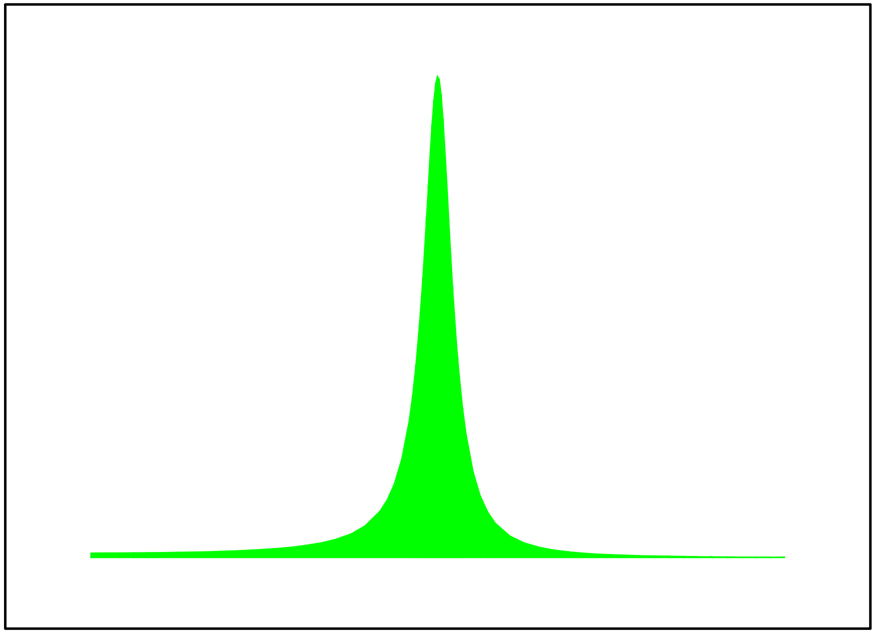
- For $m_H < 140$ GeV (preferred by precision electroweak data and supersymmetry), best decay mode at LHC is $H \to \gamma\gamma$
- QCD continuum background to this process is huge — can it contaminate the signal through interference?

LD, Siu, hep-ph/0302233

In pictures . . .

- Signal



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- Signal
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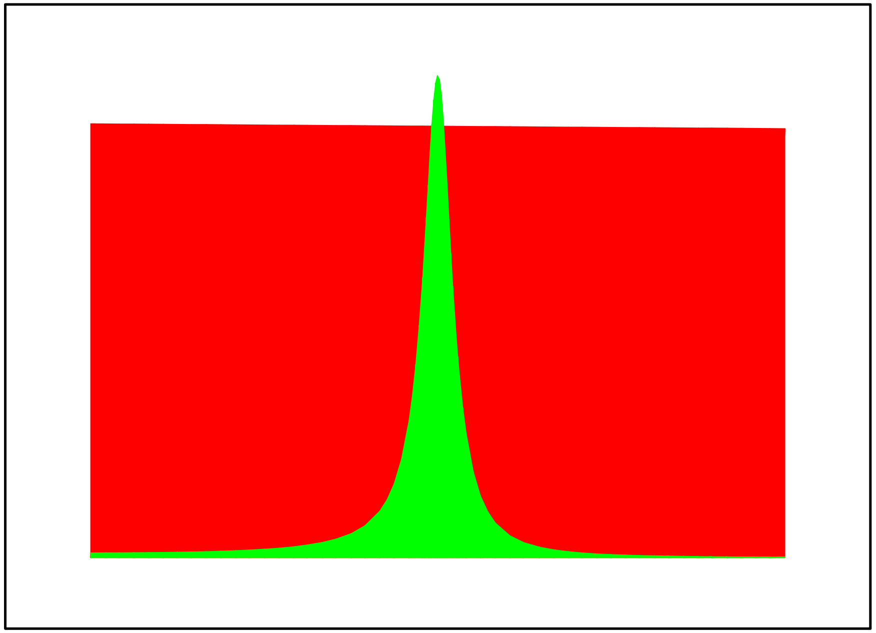

In pictures . . .

- Signal
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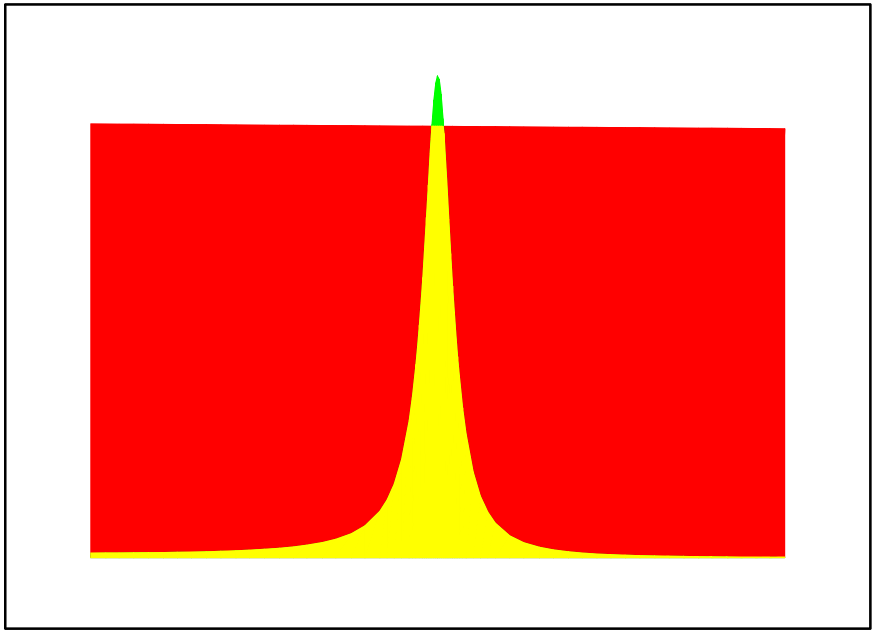
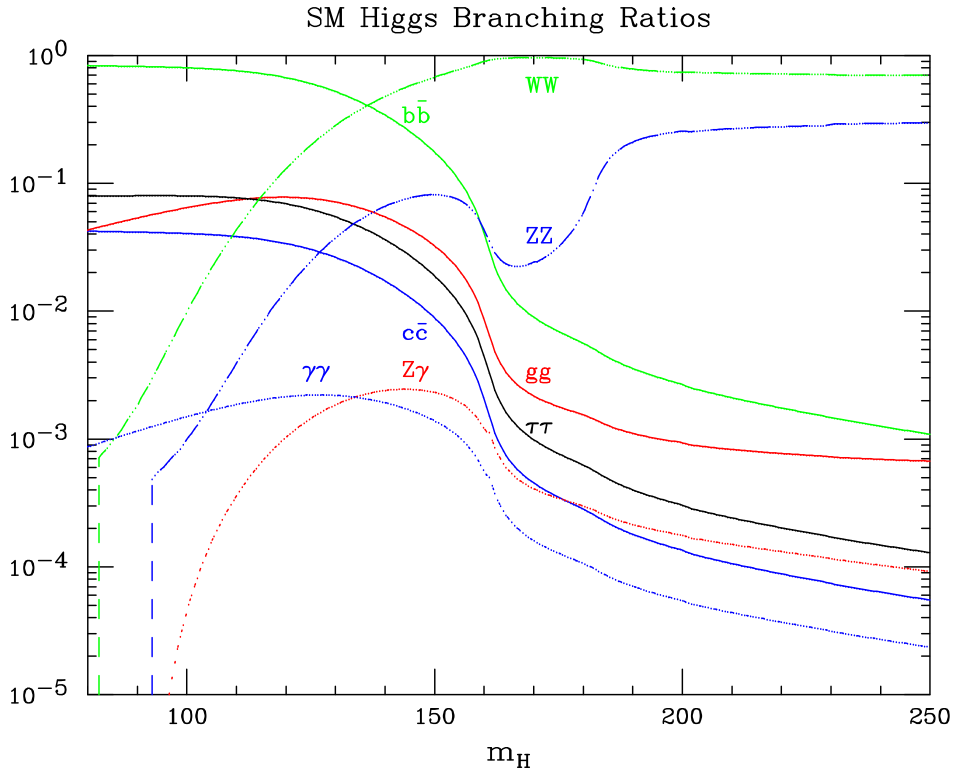
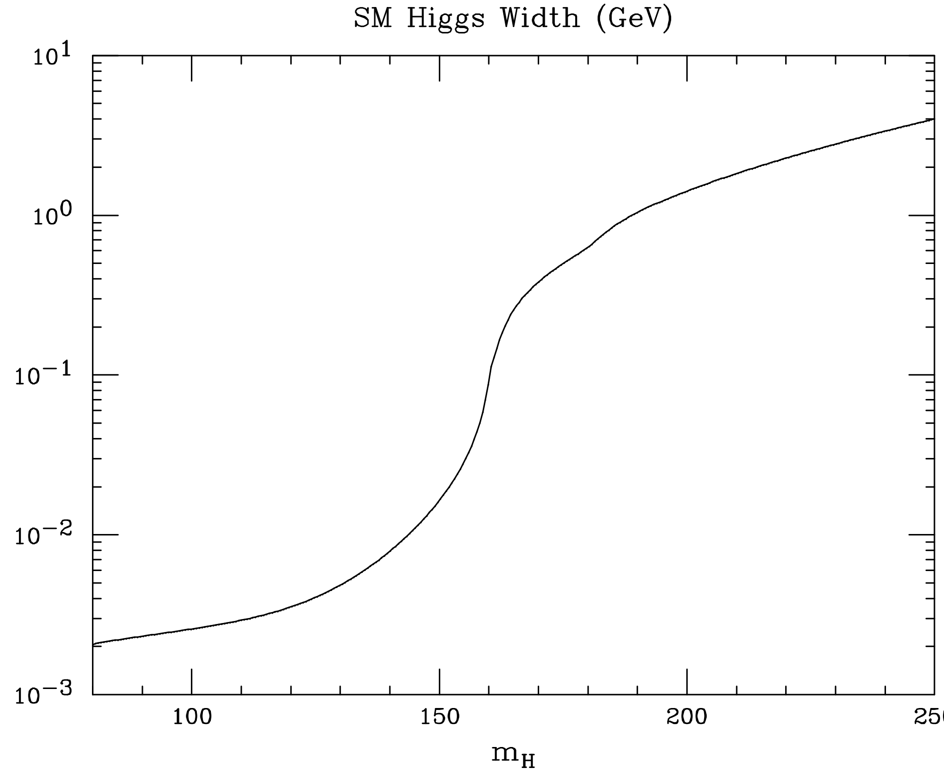
- Interference



Higgs branching ratios & width





- For $m_H < 2m_W$, Higgs resonance is narrow, $\Gamma_H \sim$ MeV
  Excellent experimental photon energy resolution, $\approx 1\%$
  $\Rightarrow \gamma\gamma$ signal visible even though $\text{Br}(H \to \gamma\gamma) \approx 10^{-3}$.

Interference effect

- General issue when extracting couplings $g_{Hii}^2 \propto \Gamma_i$ from expt. signals for various production/decay channels:

Is $$\text{Signal} = \sigma_{ii \to H} \times \text{Br}(H \to ff) = \frac{\Gamma_i \Gamma_f}{\Gamma} \qquad ?$$

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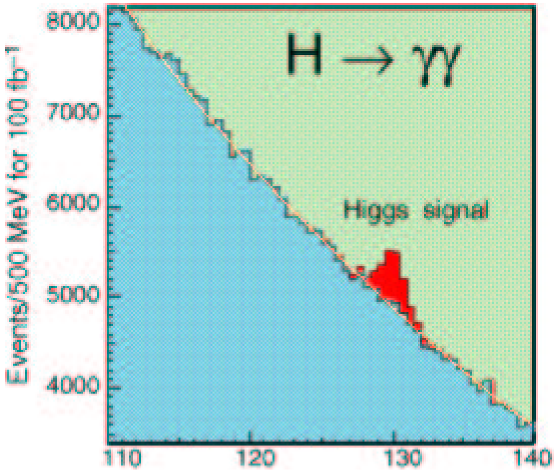
- Resonance-continuum interference negates this; how big is it for $gg \to H \to \gamma\gamma$?
- Normally interf. effects small for a narrow resonance: If expt'l resolution $\gg$ intrinsic linewidth Γ, and if you can see it at all, it must be that the intrinsic $S/B \gg 1$, right?

Back-of-envelope calculation

- $S/B \approx 1/20$ 

CMS

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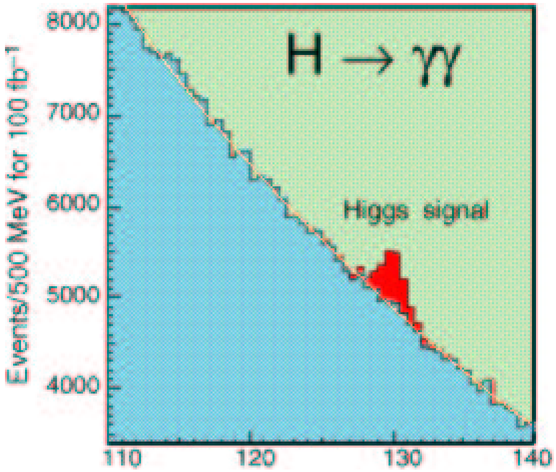

- $S/B \approx 1/20$ CMS
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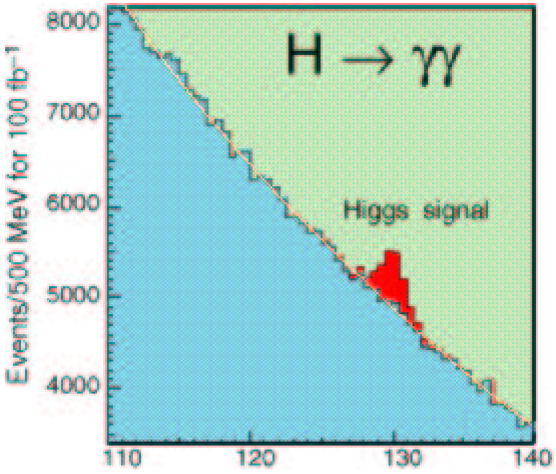

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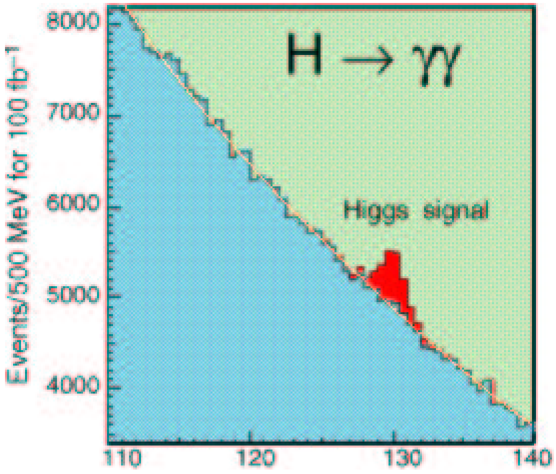

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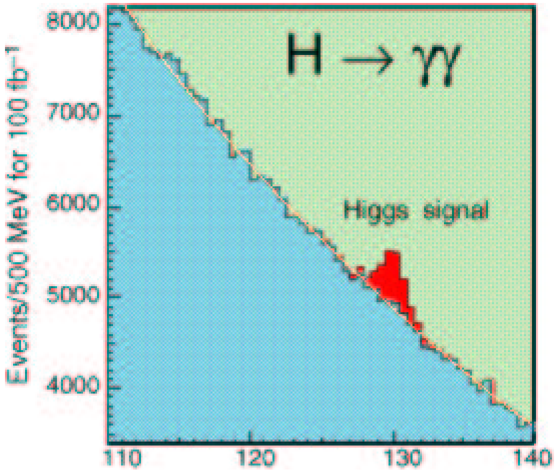

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- So intrinsic $S/B \approx 1/20 \times 1000 \times 3 \approx 150$
- Interference effect is $\approx 2\sqrt{B/S} \approx 15\%$

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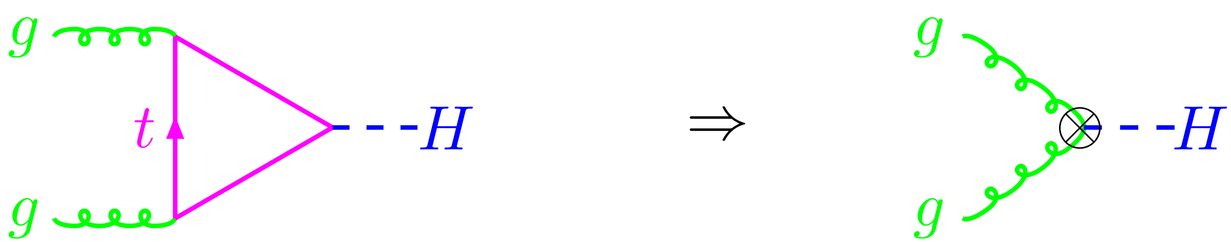
- $\sigma(\mathrm{pp} \to H + X)$ is more uncertain.

Higgs total cross section σ_H

- $\mathrm{pp} \to H + X$ at LHC (or Tevatron) is dominated by gluon-gluon fusion through a top quark loop



- NLO QCD K factor for σ_H is huge, about 1.7–1.8 at LHC.

  Djouadi, Spira, Zerwas; Dawson; Spira, Djouadi, Graudenz, Zerwas

- To make NNLO computation feasible, approximate top quark loop by effective ggH vertex ($m_H \ll 2m_t$).

  Catani, De Florian, Grazzini; Harlander, Kilgore   Harlander, Kilgore; Anastasiou, Melnikov

  Residual error from NNLO/NNLL approximation probably $\approx 15\%$ now. ($\sigma_H^{\mathrm{NNNLO}}$???)

In search of a phase

- Total $gg \to \gamma\gamma$ amplitude

$$\mathcal{A}_{gg\to\gamma\gamma} = \frac{-\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}}{\hat{s} - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\rm cont}$$

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$$- 2m_H\Gamma_H\frac{\mathrm{Im}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\rm cont}\right)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2}$$

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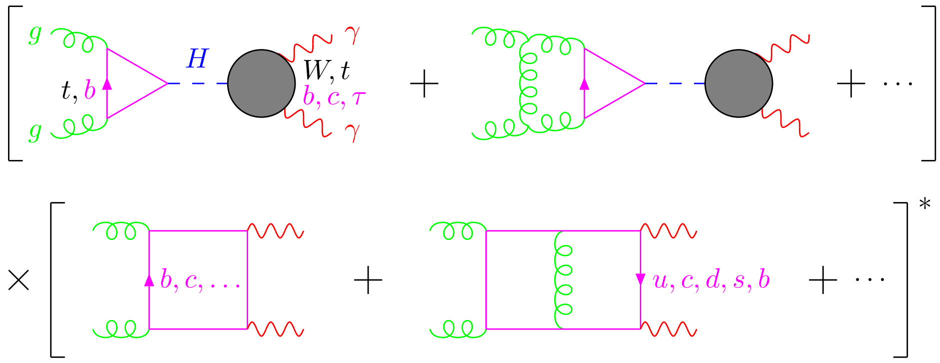
- "Im" term needs relative phase, resonance *vs.* continuum.

Source of the phase?

- Interference in diagrams:



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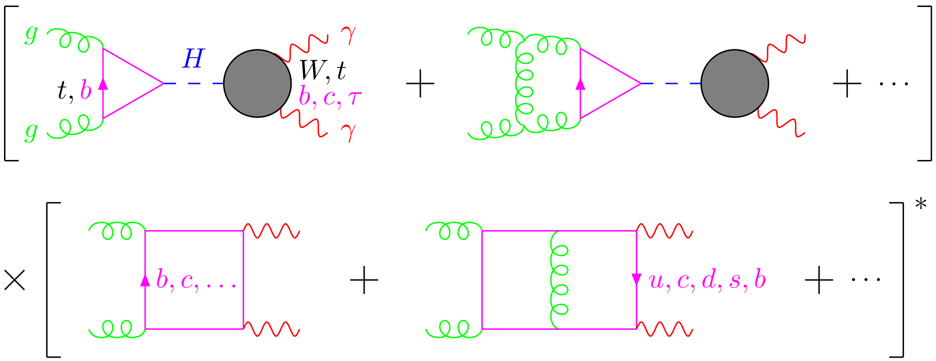

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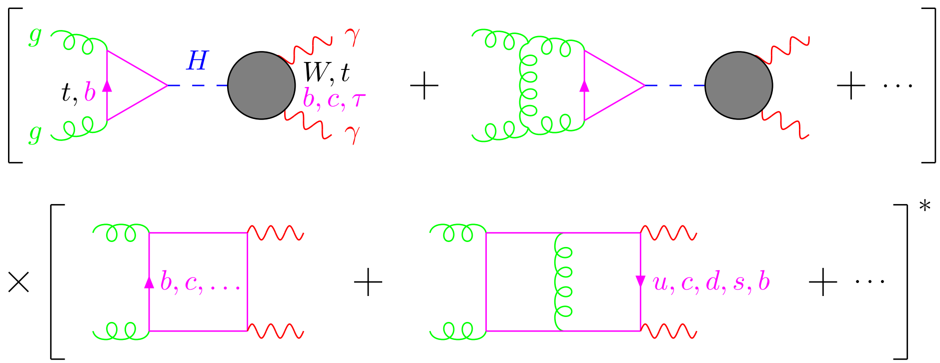

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- At 1-loop, $\mathcal{A}^*_{\rm cont}$ is also mainly **real**, because $\mathcal{A}^{\rm tree}(g^\pm g^\pm \to q\bar{q}) = \mathcal{A}^{\rm tree}(q\bar{q} \to \gamma^\pm\gamma^\pm) = 0$ for $m_q = 0$. Dicus, Willenbrock

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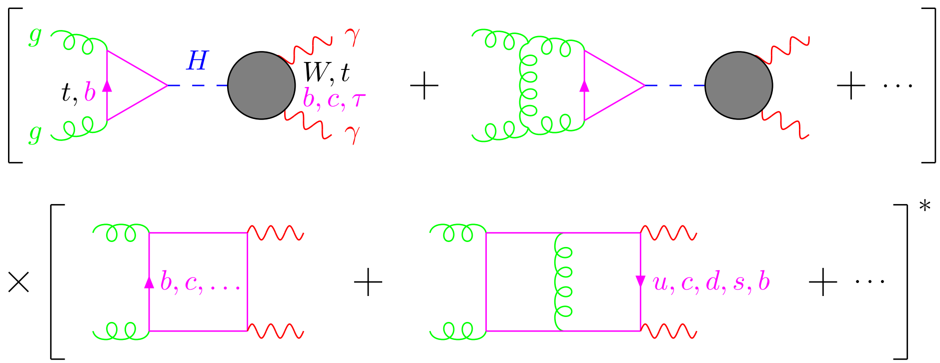

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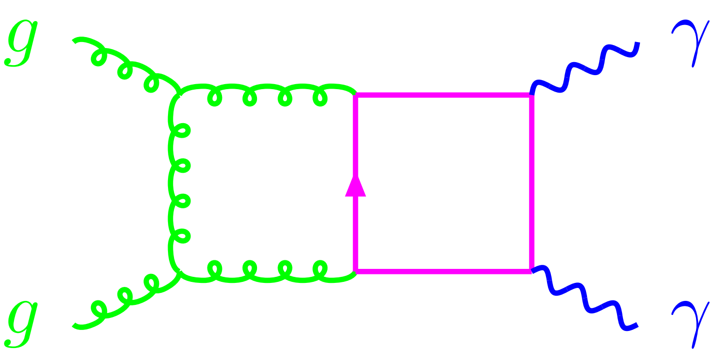
- Dominant phase is from $\mathcal{A}^{2-\rm loop}_{gg\to\gamma\gamma}$, in particular ${\rm Im}\, F^{\rm L}_{--++}$.

Need 2-loop $gg \to \gamma\gamma$ helicity amplitudes

Bern, De Freitas, LD



Also important for NLO calculation of $gg \to \gamma\gamma X$
— significant contribution to $\gamma\gamma$ continuum background.

Bern, LD, Schmidt

1-loop $gg \to \gamma\gamma$ amplitude

$$\mathcal{A}^{1-\text{loop}}_{gg\to\gamma\gamma} = 4\alpha\,\alpha_s(\mu)\delta^{a_1 a_2}\left(\sum_i Q_i^2\right)A^{(1)}(s,t)$$

- Through $\mathcal{O}(\epsilon^0)$ (note missing imaginary parts)

$$\begin{aligned}
A^{(1)}_{++++} &= A^{(1)}_{-+++} = A^{(1)}_{+-++} = A^{(1)}_{++-+} = A^{(1)}_{+++-} = 1 \\
A^{(1)}_{--++} &= -\frac{1}{2}\frac{t^2+u^2}{s^2}\left[\ln^2\left(\frac{t}{u}\right)+\pi^2\right] - \frac{t-u}{s}\ln\left(\frac{t}{u}\right) - 1 \\
A^{(1)}_{-+-+} &= -\frac{1}{2}\frac{t^2+s^2}{u^2}\ln^2\left(-\frac{t}{s}\right) - \frac{t-s}{u}\ln\left(-\frac{t}{s}\right) - 1 \\
&\quad - i\pi\left[\frac{t^2+s^2}{u^2}\ln\left(-\frac{t}{s}\right) + \frac{t-s}{u}\right] \\
A^{(1)}_{+--+} &= A^{(1)}_{-+-+}(t \leftrightarrow u)
\end{aligned}$$

- Actually need through $\mathcal{O}(\epsilon^2)$ for 2-loop case...

2-loop $gg \longrightarrow \gamma\gamma$ amplitude

$$\mathcal{A}^{2-\text{loop}}_{gg\to\gamma\gamma} = \frac{2\alpha\,\alpha_s^2(\mu)}{\pi}\delta^{a_1 a_2}\left(\sum_i Q_i^2\right)\Bigg\{ \left[\boldsymbol{I}^{(1)}(\epsilon) + \frac{11N - 2N_f}{6}\left(\ln(\mu^2/s) + i\pi\right)\right] A^{(1)}(s,t) + N F^{\text{L}}(s,t) - \frac{1}{N}F^{\text{SL}}(s,t)\Bigg\}$$

where $N = 3$, $N_f = 5$ (below m_t), and IR poles are given in dim. reg. by: Catani

$$\boldsymbol{I}^{(1)}(\epsilon) = -N\frac{e^{-\epsilon\psi(1)}}{\Gamma(1-\epsilon)}\left[\frac{1}{\epsilon^2} + \left(\frac{11}{6} - \frac{1}{3}\frac{N_f}{N}\right)\frac{1}{\epsilon}\right]\left(\frac{\mu^2}{-s}\right)^{\epsilon}$$

Now let

$$x = \frac{t}{s}, \quad y = \frac{u}{s}, \quad X = \ln\left(-\frac{t}{s}\right), \quad Y = \ln\left(-\frac{u}{s}\right)$$

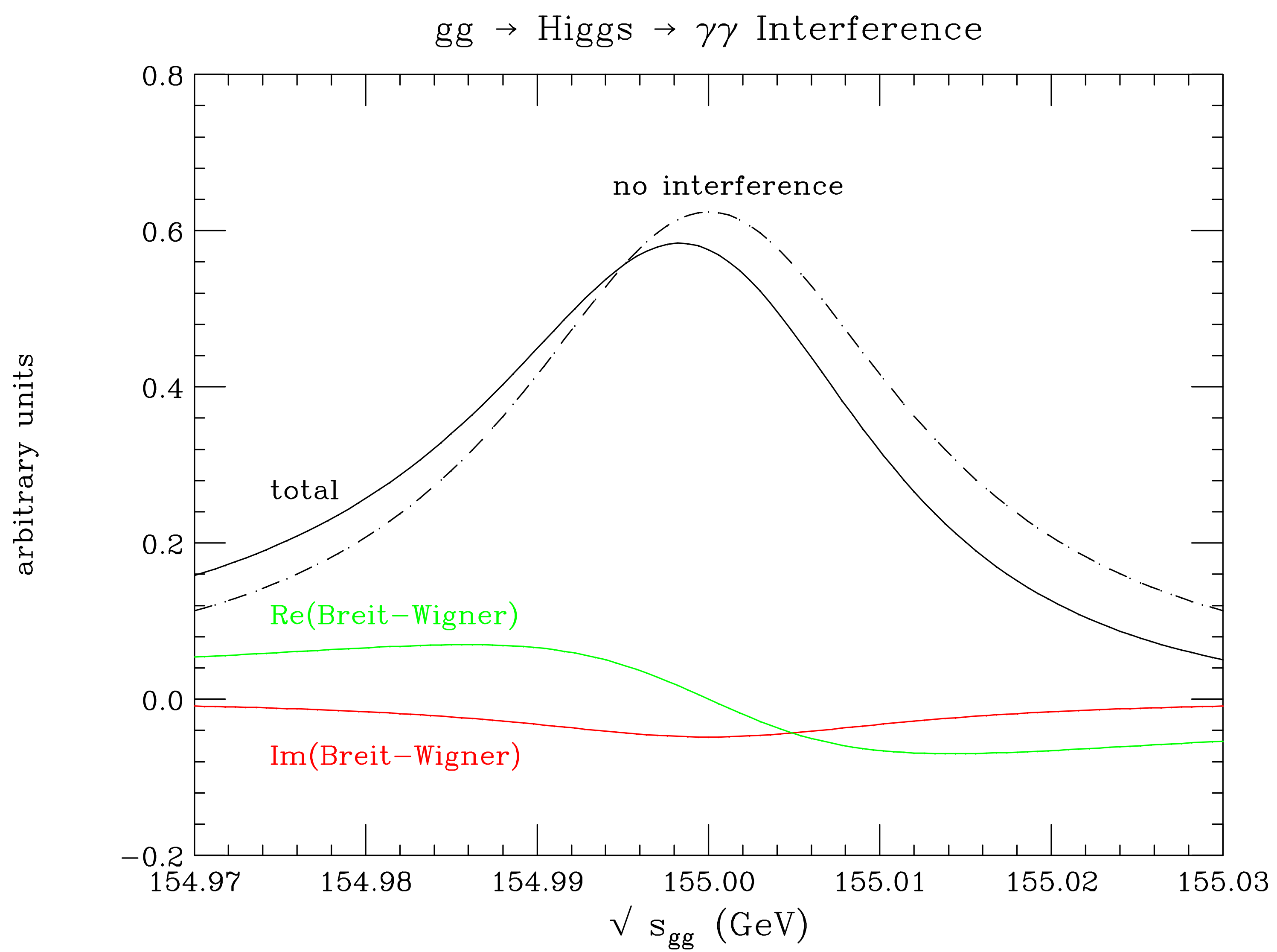
Relevant finite terms in $\mathcal{A}^{2-\mathrm{loop}}_{gg\to\gamma\gamma}$

$$F^{\mathrm{L}}_{++++} = \frac{1}{2}$$

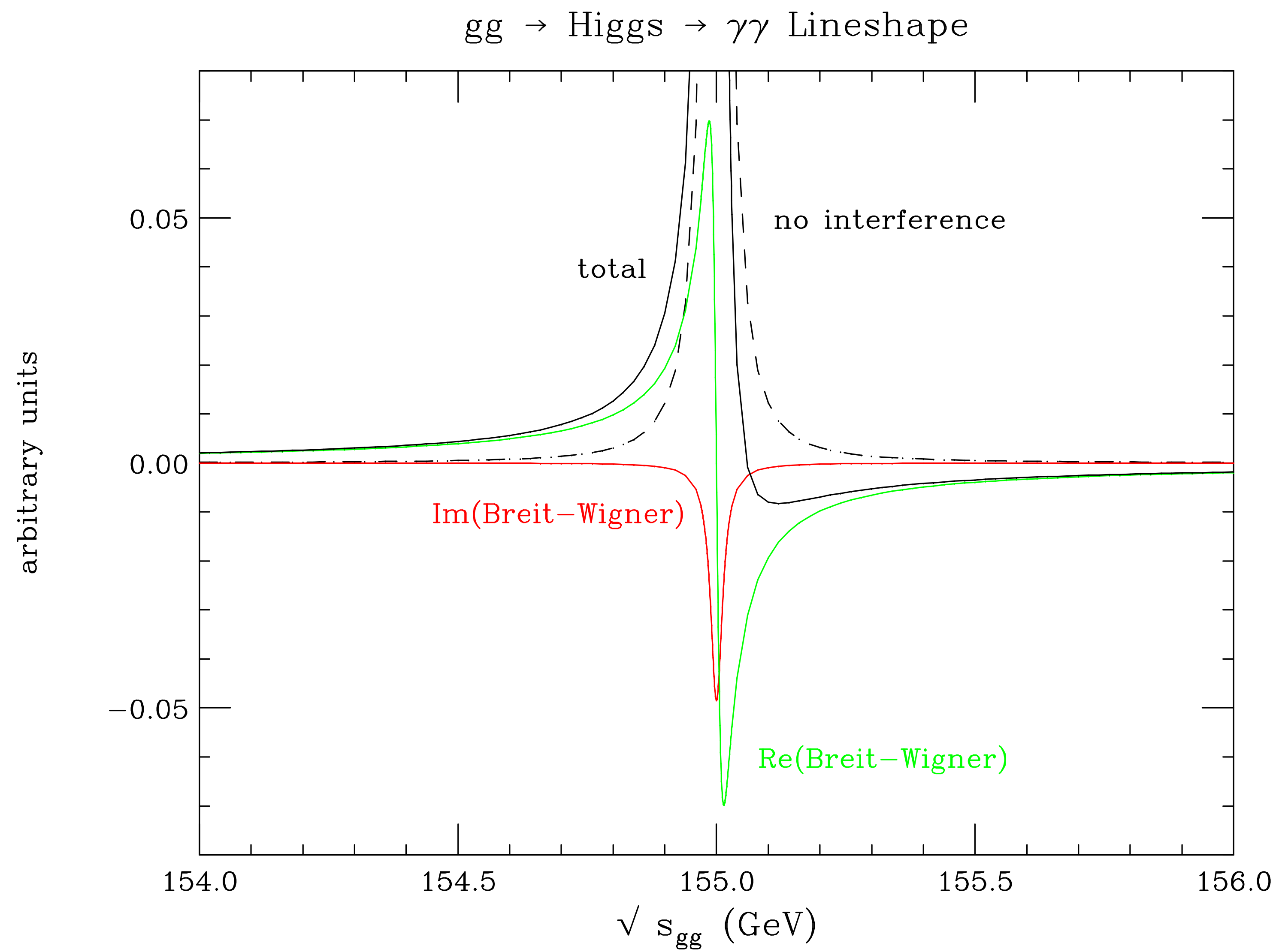
$$\begin{aligned}
F^{\mathrm{L}}_{--++} = & -(x^2+y^2)\Big[4\mathrm{Li}_4(-x) + (Y-3X-2i\pi)\mathrm{Li}_3(-x) \\
& + ((X+i\pi)^2+\pi^2)\mathrm{Li}_2(-x) + \frac{1}{48}(X+Y)^4 \\
& + i\frac{\pi}{12}(X+Y)^3 + i\frac{\pi^3}{2}X - \frac{\pi^2}{12}X^2 - \frac{109}{720}\pi^4\Big] \\
& + \frac{1}{2}x(1-3y)\Big[\mathrm{Li}_3(-x/y) - (X-Y)\mathrm{Li}_2(-x/y) - \zeta_3 + \frac{1}{2}Y((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{4}x^2\Big[(X-Y)^3 + 3(Y+i\pi)((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{8}\left(14(x-y) - \frac{8}{y} + \frac{9}{y^2}\right)((X+i\pi)^2+\pi^2) \\
& + \frac{1}{16}(38xy-13)((X-Y)^2+\pi^2) - \frac{\pi^2}{12} - \frac{9}{4}\left(\frac{1}{y}+2x\right)(X+i\pi) + \frac{1}{4} \\
& + \Big\{t \leftrightarrow u\Big\}
\end{aligned}$$

note imaginary parts!

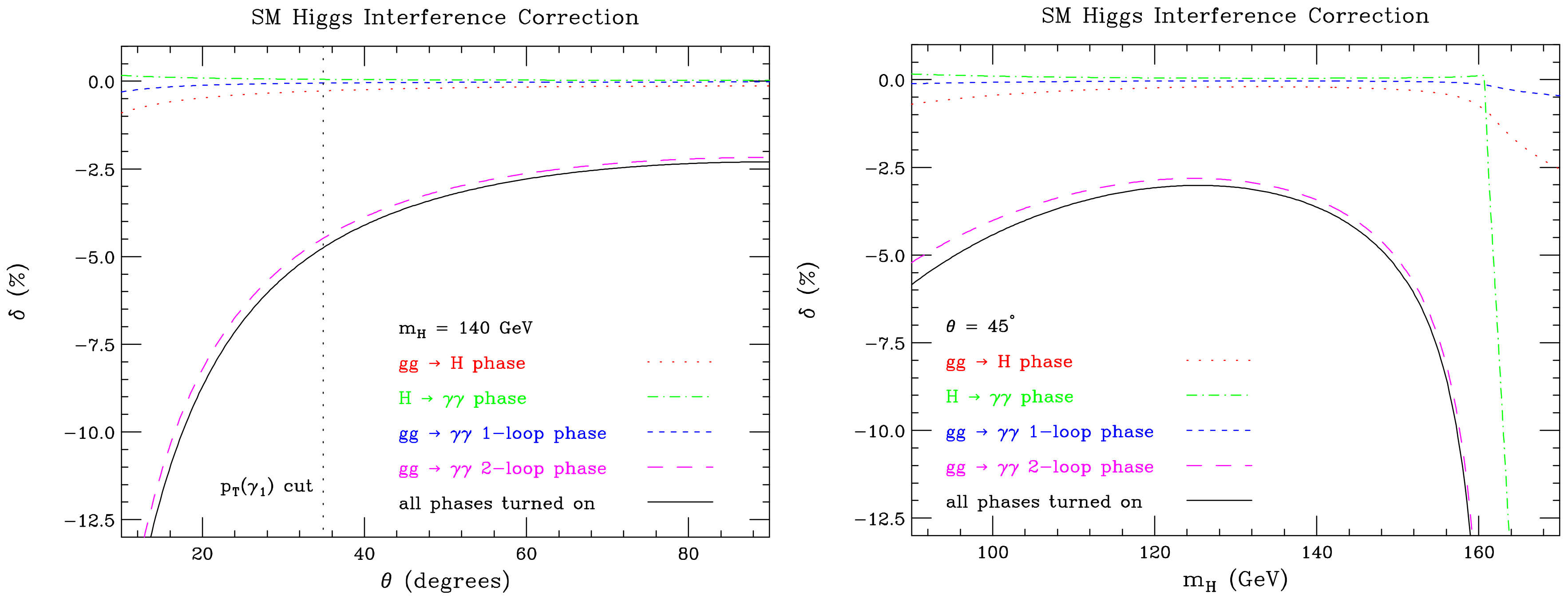
Close-up of Higgs resonance



Not-so-close-up of Higgs resonance

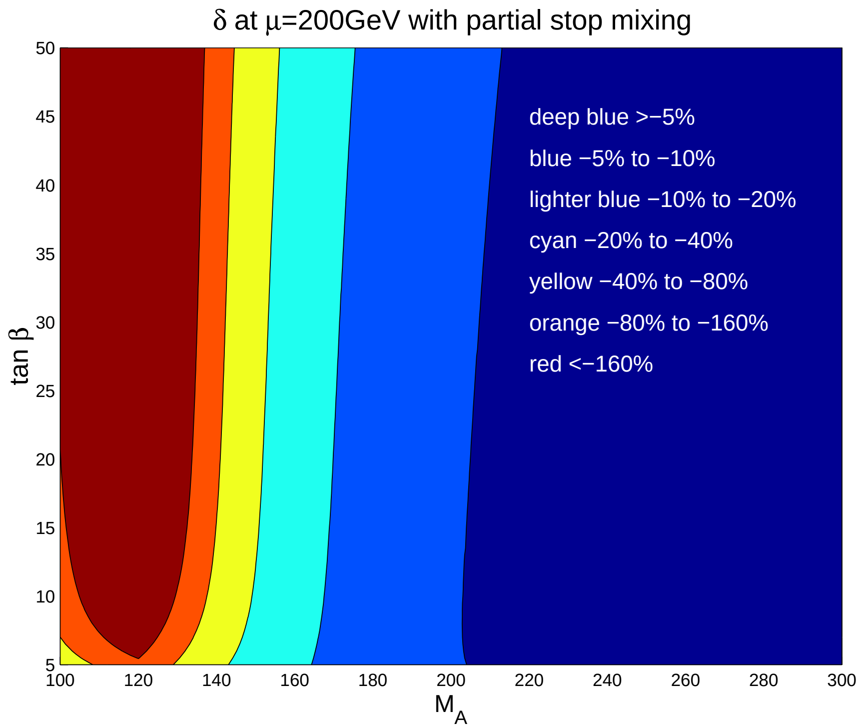


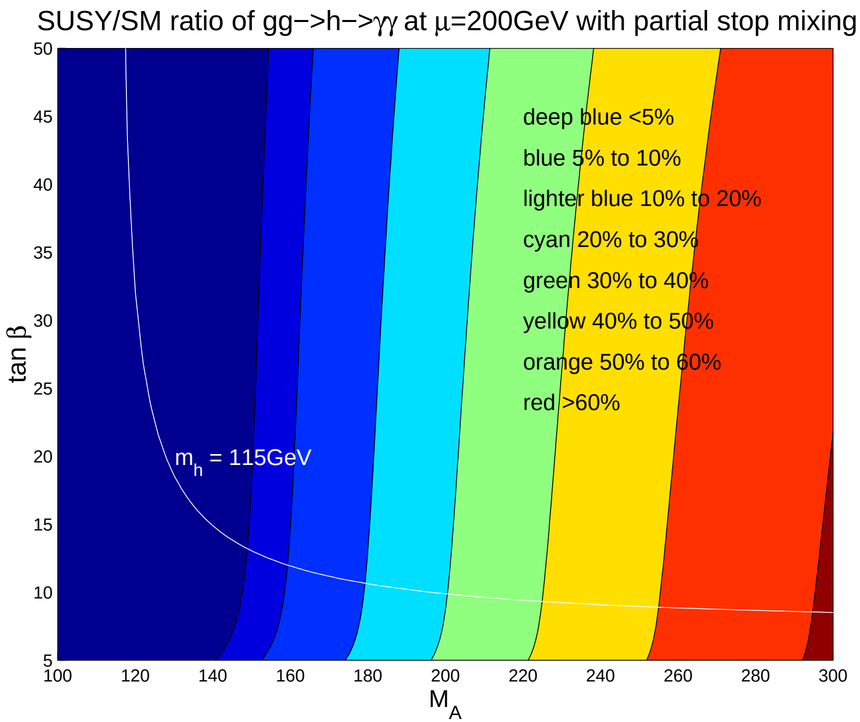
Percentage correction to SM Higgs signal



- Effect is $-(2-6)\%$ over region where $\gamma\gamma$ is visible.
- Gets very large near WW threshold.
  (We checked that phase from $H \to WW^* \to \gamma\gamma$ is not significant here.)

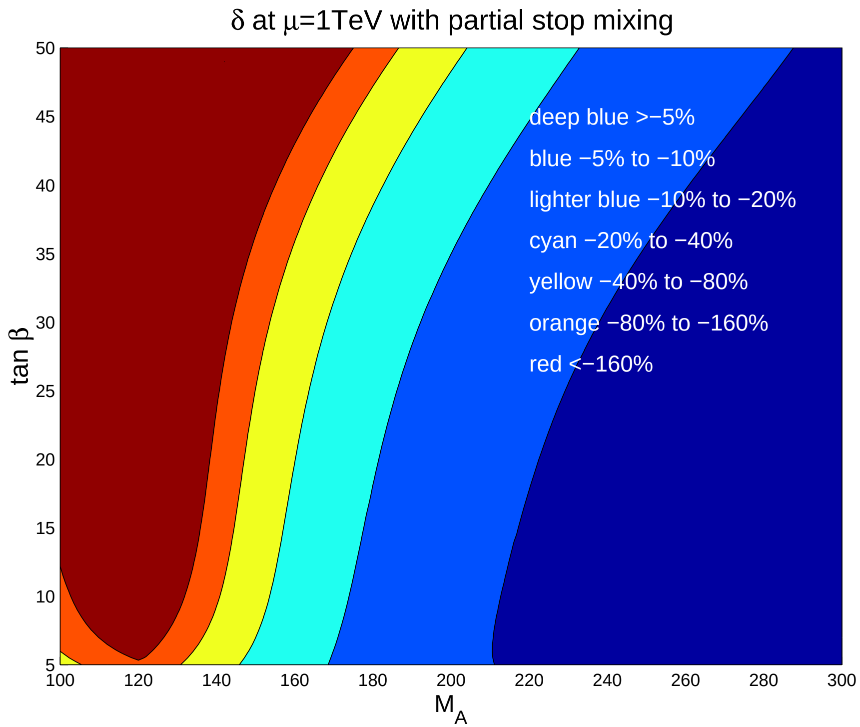
Preliminary study of MSSM

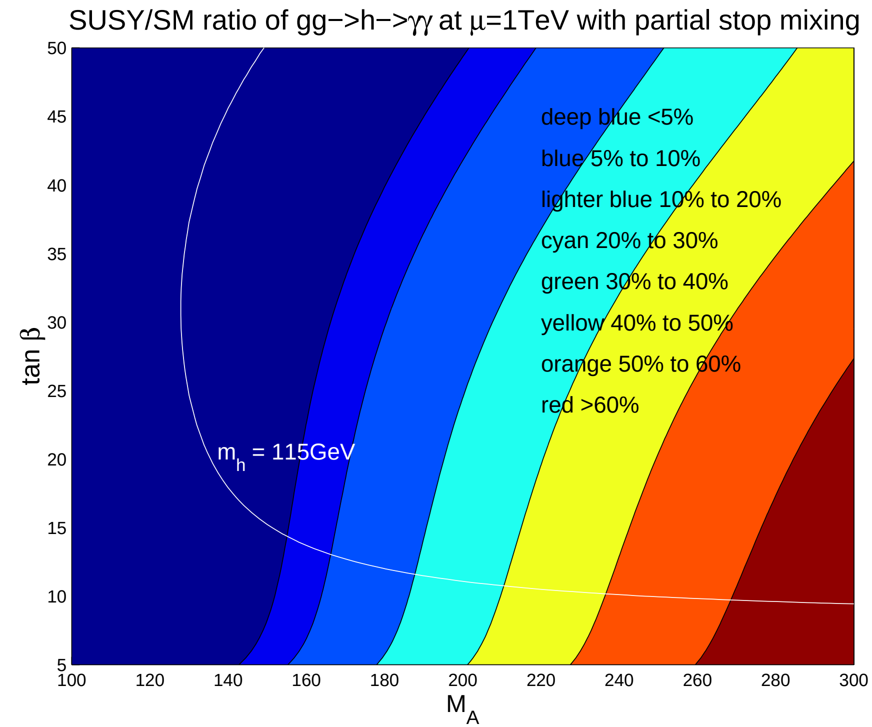




- Effect larger if $Hb\bar{b}$ coupling increases, driving up Γ_H.
- But visibility of signal is also drops as $\mathrm{Br}(H \to \gamma\gamma)$ drops.
- Here $X_b = X_t = 1.2$ TeV, $M_{\mathrm{SUSY}} = 1$ TeV, $\mu = 200$ GeV.

Preliminary study of MSSM (cont.)





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- Effect is destructive in the SM, though $-(2-6)\%$ is below presently anticipated th. & expt. uncertainties.
- Effect can get larger in MSSM, for example, in regions where the $\gamma\gamma$ signal is still visible.
- Further study of effects in MSSM, other Higgs models, and in selected other channels in the (MS)SM is warranted.