Signal/background interference in the di-photon Higgs signal at the LHC

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LHC-The First Part of the Journey

KITP @ UC Santa Barbara

July 8, 2013

1208.1533 SPM

1303.3342 SPM

1305.3854 Lance Dixon and Ye Li

What we learned since July 4, 2012:

- A Higgs scalar exists near $M_H = 125.6$ GeV
- Consistent with Standard Model Higgs
- No new physics that could be associated with non-Standard-Model-ness of the EWSB sector

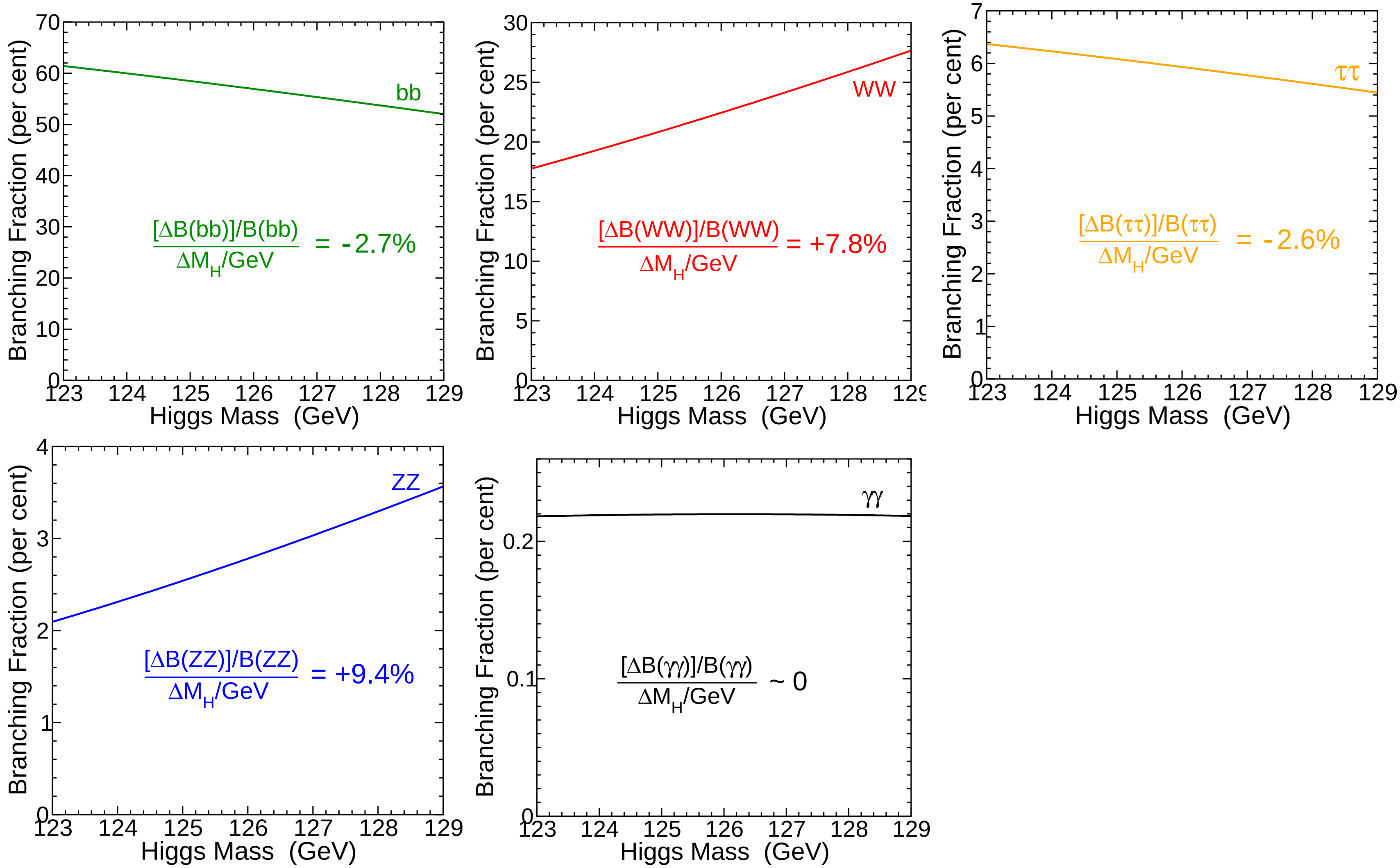
Therefore, it is sensible to assume that this is indeed the Standard Model Higgs, and nothing more.

So, today I will.

We will want to know M_H as accurately as possible:

- The last parameter in the (old) Standard Model
- Stability of the Standard Model vacuum
- Self-coupling vanishes at high scales ($\lambda = 0$) ?
- Standard candle for future work (new physics decaying to H)
- The Higgs BR's (especially to ZZ and WW) are sensitive to mass
- Are $H \to \gamma\gamma$ and $H \to ZZ$ really the same Higgs?

Dependence of Standard Model Higgs branching ratio predictions on M_H, from HDECAY (Djouadi, Kalinowski, Spira):



Need to confirm that $M_{H\to ZZ}$ and $M_{H\to\gamma\gamma}$ are really the same.

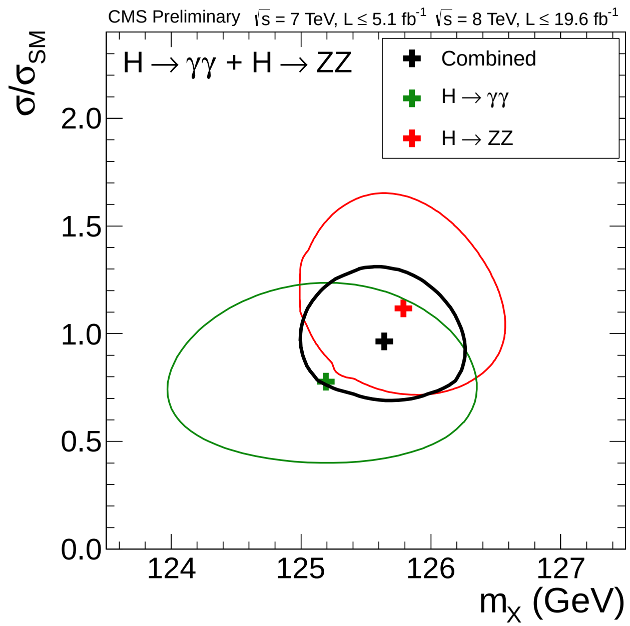
Interesting counterexamples with almost degenerate Higgses:

Gunion, Jiang, Kraml 1207.1545, 1208.1817

Ferreira, Haber, Santos, Silva 1211.3131

There could be two states near 126 GeV, with $M_{H\to ZZ} \neq M_{H\to\gamma\gamma}$ and $\sigma_{\gamma\gamma}/\sigma_{\gamma\gamma}^{\rm SM} \neq \sigma_{ZZ}/\sigma_{ZZ}^{\rm SM}$.

But, note that so far ATLAS and CMS see **opposite** orderings for $M_{H\to ZZ}$ and $M_{H\to\gamma\gamma}$, compared to each other.

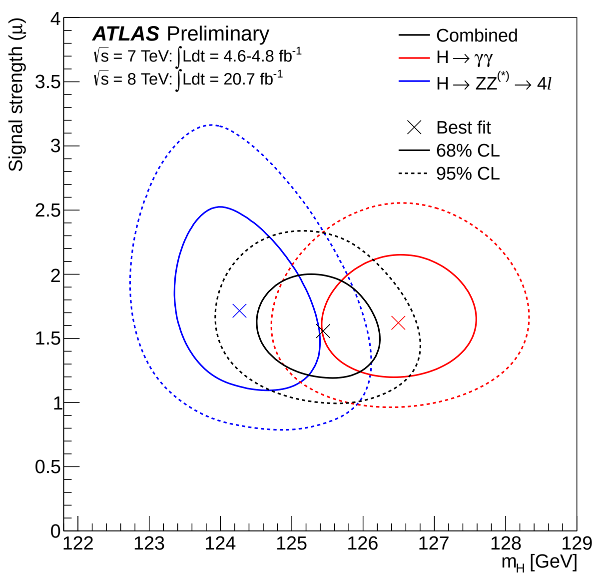


CMS M_H, stat, syst:

$125.4 \pm 0.5 \pm 0.6 \quad (H \to \gamma\gamma)$

$125.8 \pm 0.5 \pm 0.2 \quad (H \to ZZ^*)$

$125.7 \pm 0.3 \pm 0.3$ (combined)



ATLAS M_H, stat, syst:

$126.8 \pm 0.2 \pm 0.7 \quad (H \to \gamma\gamma)$

$124.3 \ {}^{+0.6}_{-0.5} \ {}^{+0.5}_{-0.3} \quad (H \to ZZ^*)$

$125.5 \pm 0.2 \ {}^{+0.5}_{-0.6}$ (combined)

It has been said that LHC might eventually be able to measure M_H to 100 MeV, or perhaps 50 MeV with high luminosity upgrade.

This will depend on reduction of systematic uncertainties. No recent citeable studies?

Don't know how to judge this, so I will simply be vaguely optimistic.

Consider the impact of quantum interference between the signal

$$gg \to H \to \gamma\gamma$$

and the continuum background with the same initial and final state.

For most purposes, the narrow width approximation is used:

$$\frac{1}{(\hat{s} - M_H^2)^2 + M_H^2\Gamma_H^2} \approx \frac{\pi}{M_H\Gamma_H}\delta(\hat{s} - M_H^2)$$

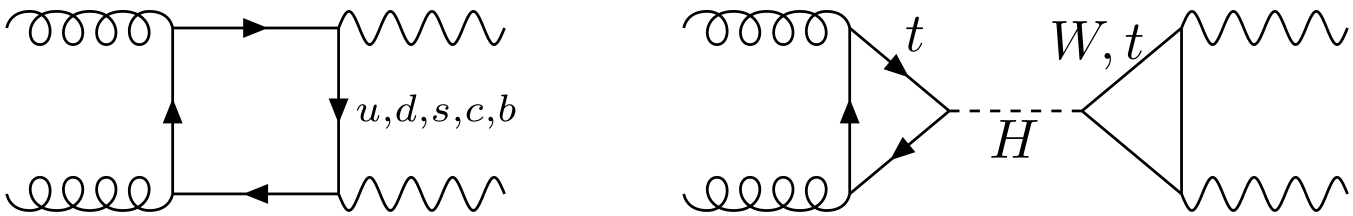
Because $\Gamma_H \approx 4.2$ MeV $\approx (3.4 \times 10^{-5})M_H$, this is usually fine.

However, not for interference effects.

See also work by Glover, van der Bij 1989; Campbell, Ellis, Williams 1107.5569; Kauer 1201.1667; Kauer, Passarino 1206.4803; Passarino 1206.3824; Kauer 1305.2092.

Continuum and Higgs resonance amplitudes for

$gg \to \gamma\gamma$:



$$\mathcal{M} = A_{gg\gamma\gamma} - \frac{A_{ggH} A_{\gamma\gamma H}}{\hat{s} - M_H^2 + i M_H \Gamma_H}$$

Usually, interference between narrow-width resonant and continuum amplitudes can be safely neglected.

However, in this case, the signal amplitude is loop-suppressed compared to the background amplitude.

There are two orthogonal issues for signal/background interference:

- **Size: Contribution of interference to total $H \to \gamma\gamma$ cross-section.** Dixon and Siu 0302233 showed that the leading effect arises from the 2-loop order correction to the continuum amplitude, where the mass suppression found for the relevant polarizations at 1-loop order are absent. Net effect is to decrease total cross-section by few per cent.

- **Shape: Contribution of interference to $H \to \gamma\gamma$ mass distribution.** After experimental resolution effects, there remains a small but (eventually) measurable effect.

Size: LO interference parton-level cross-sections

$$\begin{aligned}\Delta\hat{\sigma}_{gg\to\gamma\gamma} &= -\left[\frac{\hat{s}-M_H^2}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]2\mathrm{Re}[A_{ggH}A_{\gamma\gamma H}A^*_{gg\gamma\gamma}] \\ & \quad -\left[\frac{M_H\Gamma_H}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]2\mathrm{Im}[A_{ggH}A_{\gamma\gamma H}A^*_{gg\gamma\gamma}]\end{aligned}$$

- First term vanishes after $\hat{s}$ integration in narrow-width approximation, because odd in $\hat{s}-M_H^2$.
- Second term small, because of Γ_H factor and because of quark mass suppression in $\mathrm{Im}[A_{gg\gamma\gamma}]$ at leading order for those polarizations that can interfere with H.

Dicus and Willenbrock 1988, Dixon and Siu 0302233

Shape: Consider the leading contributions to the $\gamma\gamma$ mass distribution:

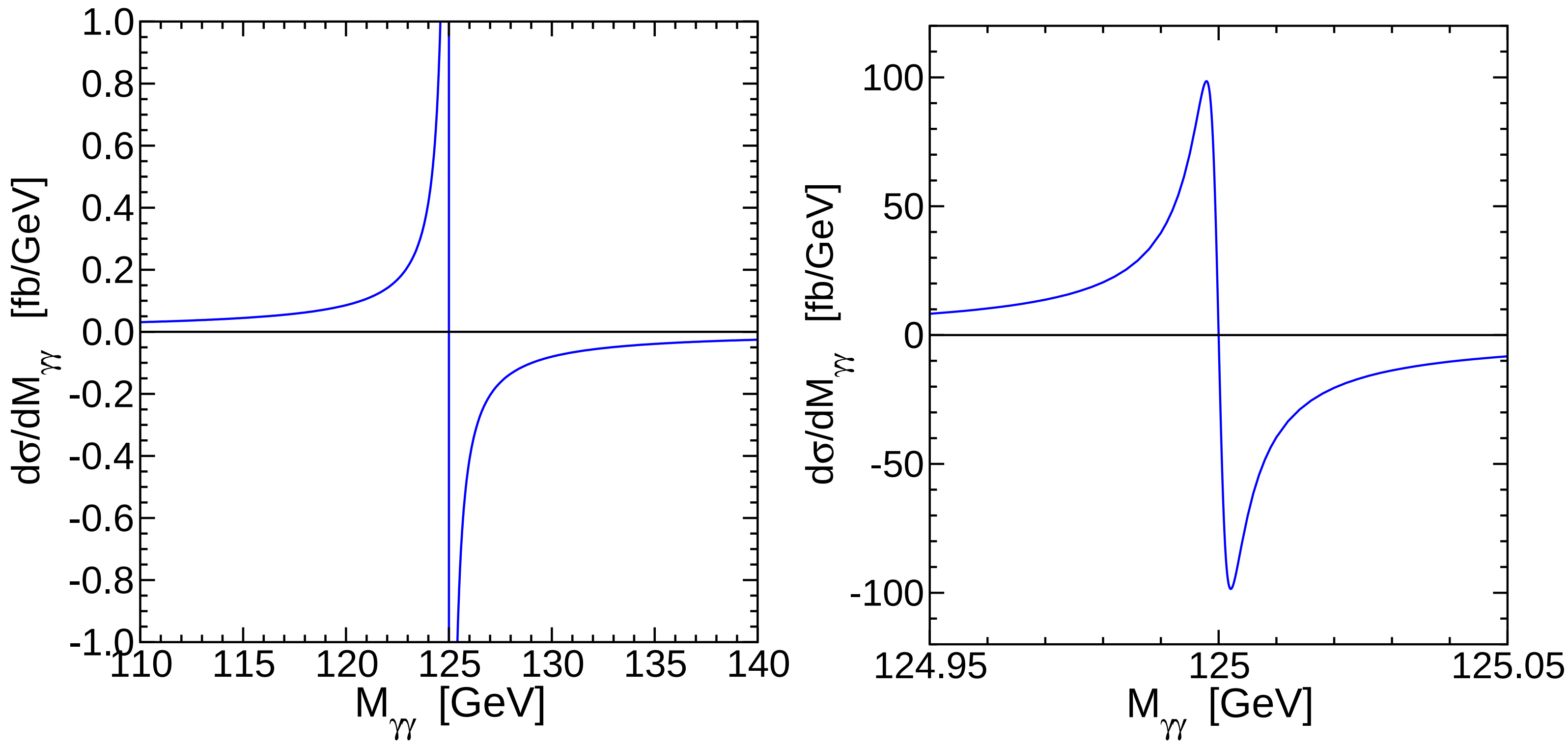
$$\frac{d^2\sigma_{pp\to\gamma\gamma}^{H,\,\mathrm{resonant}}}{d(\sqrt{\hat{s}})dz} = \frac{G(\hat{s})}{128\pi\sqrt{\hat{s}}}|A_{ggH}A_{\gamma\gamma H}|^2\left[\frac{1}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]$$

$$\frac{d^2\sigma_{pp\to\gamma\gamma}^{\mathrm{int}}}{d(\sqrt{\hat{s}})dz} = -\frac{G(\hat{s})}{64\pi\sqrt{\hat{s}}}\mathrm{Re}[A_{ggH}A_{\gamma\gamma H}A_{gg\gamma\gamma}^*]\left[\frac{\hat{s}-M_H^2}{(\hat{s}-M_H^2)^2+M_H^2\Gamma_H^2}\right]$$

The interference leads to a surplus of events for $\hat{s} < M_H^2$ and a deficit for $\hat{s} > M_H^2$, shifting the $\gamma\gamma$ mass distribution lower than it would be without interference.

Interference contribution, before including experimental resolution:

close-up:

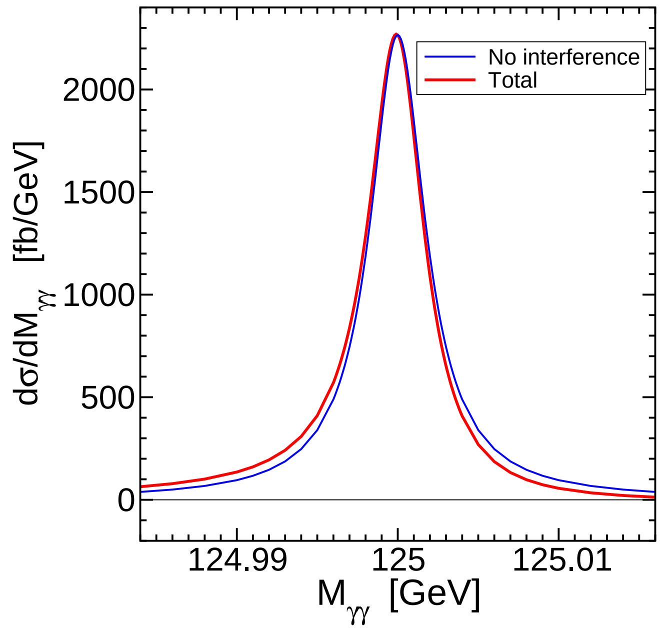


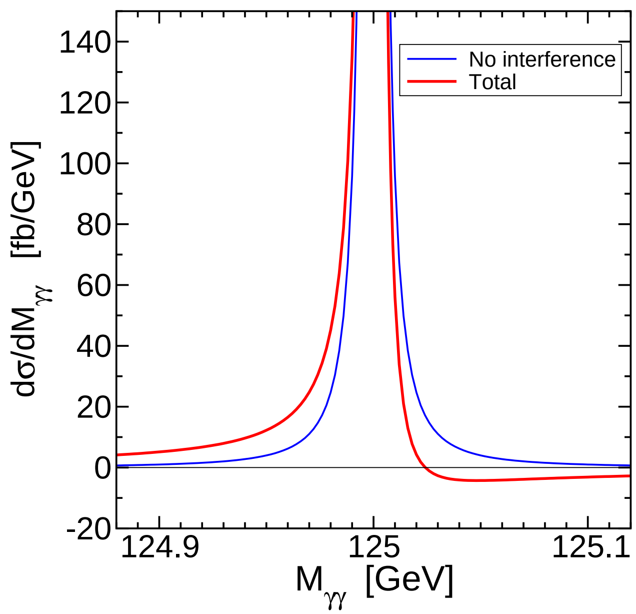
There is a very sharp peak/dip with maximum at $M_H - \Gamma_H/2$ and minimum at $M_H + \Gamma_H/2$.

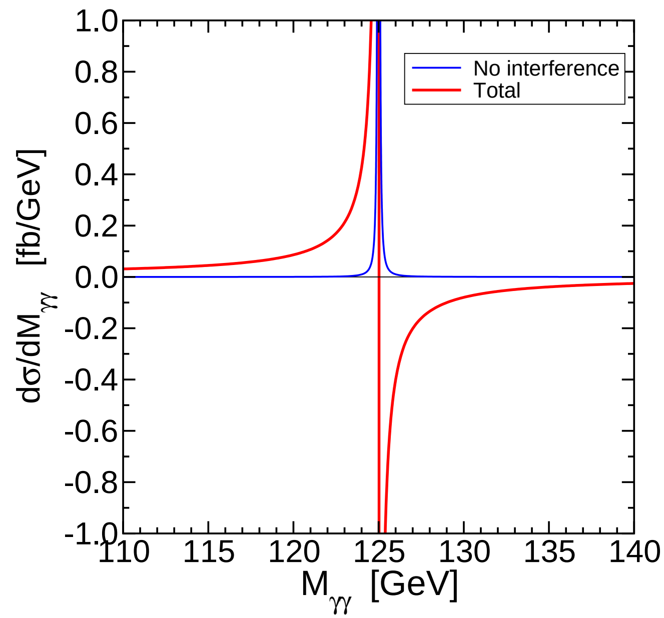
Much, but not all of this structure will be washed out by detector resolution effects.

Signal with and without interference, **before smearing**.

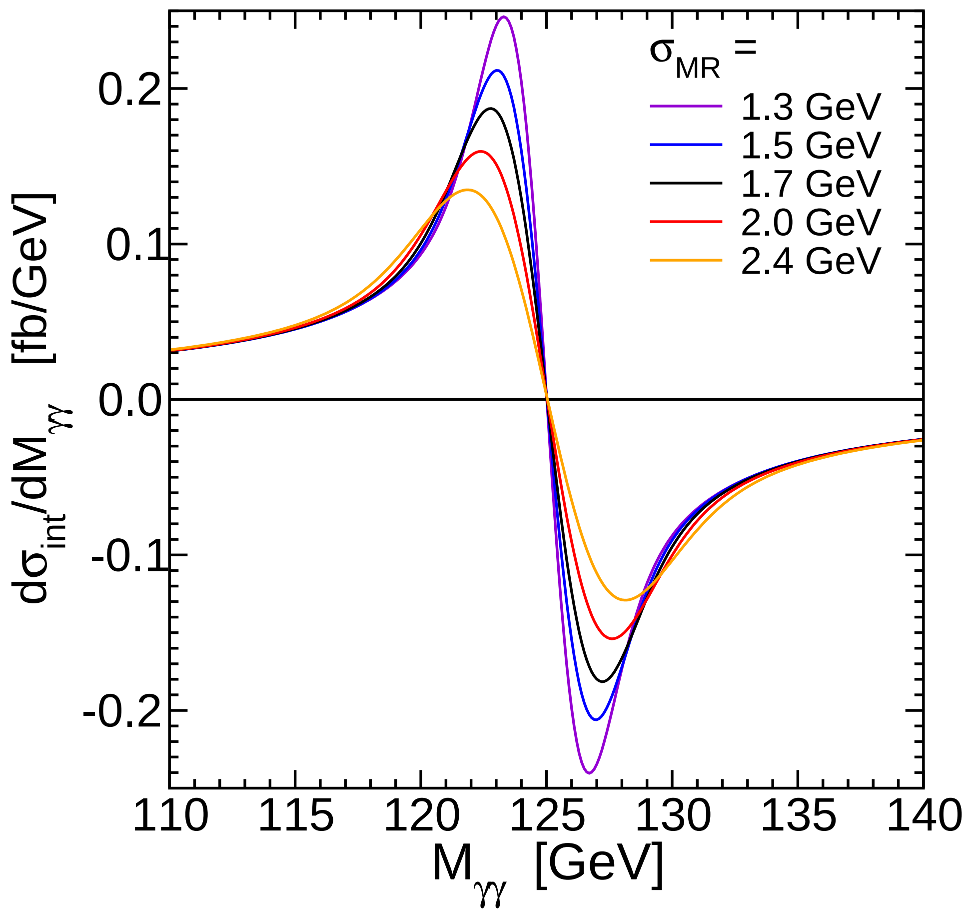
These are all exactly the same plot, just with different scales on the axes.





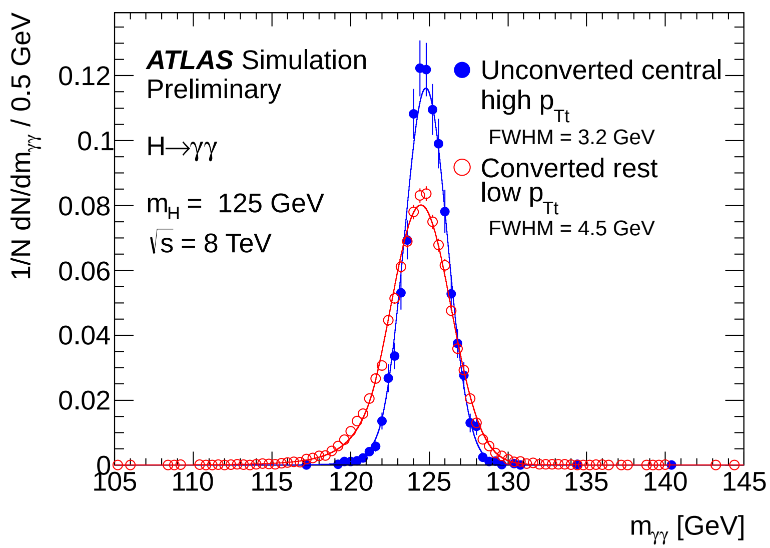


Now, the interference after smearing by various Gaussian mass resolutions:



The Gaussian smearing is used as a rough approximation to the real world situation, where the diphoton mass response is different in different parts of the detectors, depends on photon conversions, and is certainly not quite Gaussian. . .

In the Real World: not Gaussian, low mass tail.



ATLAS models with a "Crystal Ball" lineshape, dependent on 4 parameters σ_{CB}, α, n, δ_{M_H}.

$$Ne^{-t^2/2} \qquad \text{(if } t > -\alpha\text{)}$$

$$N'(n/\alpha - \alpha - t)^{-n} \qquad \text{(if } t > -\alpha\text{).}$$

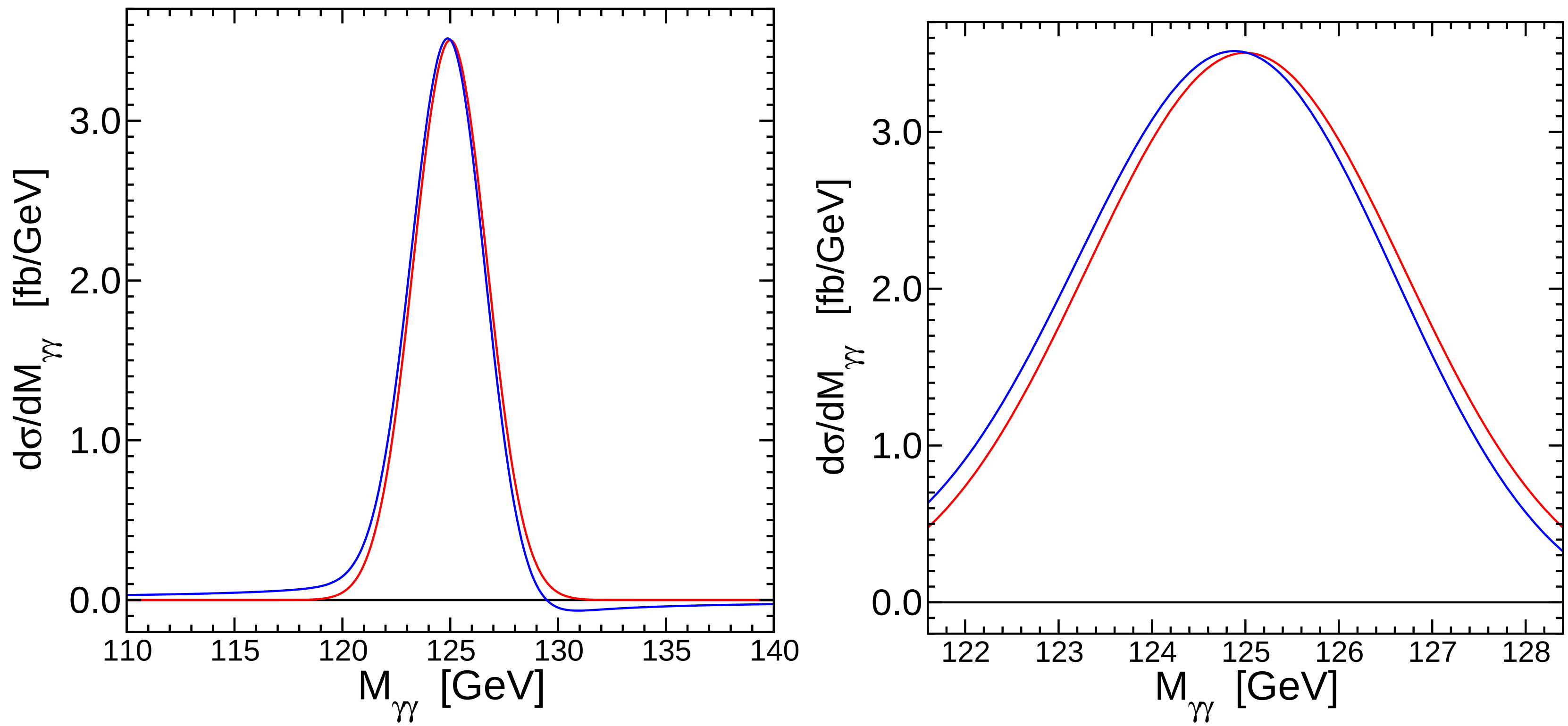
Here $t = (M_{\gamma\gamma} - M_H - \delta_{M_H})/\sigma_{CB}$.

Too complicated and mysterious for theorists (me) to model correctly.

I use pure Gaussian instead; results should be qualitatively similar.

Compare signal with and without interference (for $\sigma_{\rm MR} = 1.7$ GeV):

close-up:

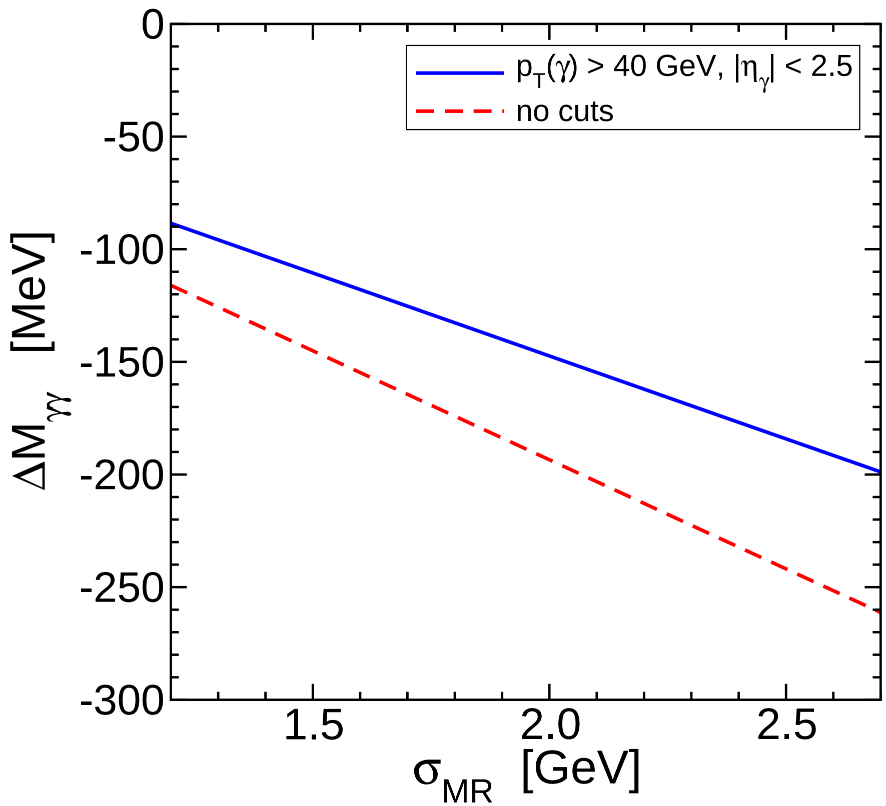


By eyeball, the shift is of order $\Delta M_{\gamma\gamma} \sim -150$ MeV.

After semi-realistic parton-level cuts:

- $p_T(\gamma) > 40$ GeV,
- $|\eta_\gamma| < 2.5$,

the shift $\Delta M_{\gamma\gamma}$ as a function of $\sigma_{\rm MR}$, obtained by simple fits to Gaussians with same width used to do the smearing:



More accuracy will depend on exactly how the distribution is fitted. (Not simple, not the same for ATLAS and CMS!)

Counterintuitive feature: the mass shift **increases** with $\sigma_{\rm MR}$.

Two comments:

• Using a different prescription for the lineshape, such as the “running width” prescription

$$\frac{1}{(\hat{s}^2 - M_H^2)^2 + M_H^2\Gamma_H^2} \quad \rightarrow \quad \frac{1}{(\hat{s}^2 - M_H^2)^2 + \hat{s}[\Gamma_H(\hat{s})]^2}$$

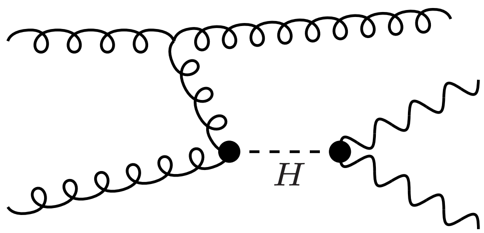
will give almost identical results, because the width is tiny compared to the experimental resolution.

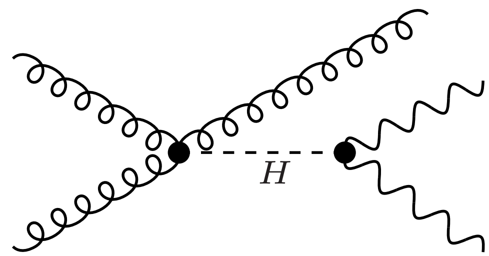
• Results for ΔM_H are nearly independent of choices of factorization and renormalization scales and α_S. At leading order, they exactly cancel out because they enter the resonant (“Higgs signal”) and continuuum (“background”) in the same way.

Previous was for LO $pp \to \gamma\gamma$.

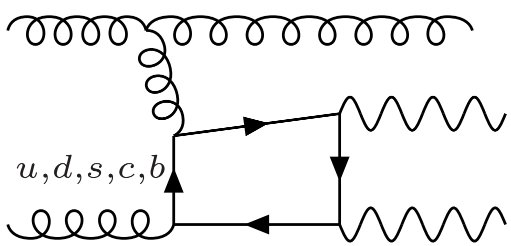
Now consider interference for $pp \to jH$, with a p_T cut on the jet.

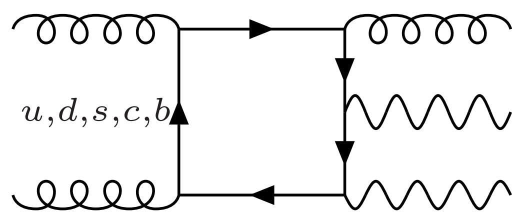
$gg \to Hg \to g\gamma\gamma$:





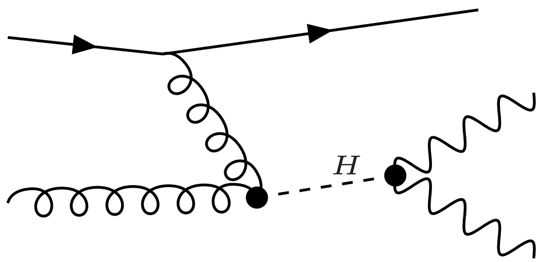
interfere with



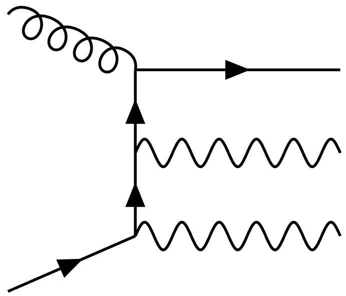


Also have parton-level processes initiated by quarks,

$gQ \to QH \to Q\gamma\gamma$ and $Q\overline{Q} \to gH \to g\gamma\gamma$ (tiny).



interferes with



Here the background is tree-level, so that the Higgs-background interference is naively **more** important compared to the pure Higgs signal. But quark PDFs are much smaller.

Buenos Aires group of de Florian, Fidanza, Hernández-Pinto, Mazzitelli, Rotstein-Habarnau, and Sborlini have also done this (using different methods), in `1303.1397`. We agree: mass shift $\Delta M_H > 0$; opposite of LO.

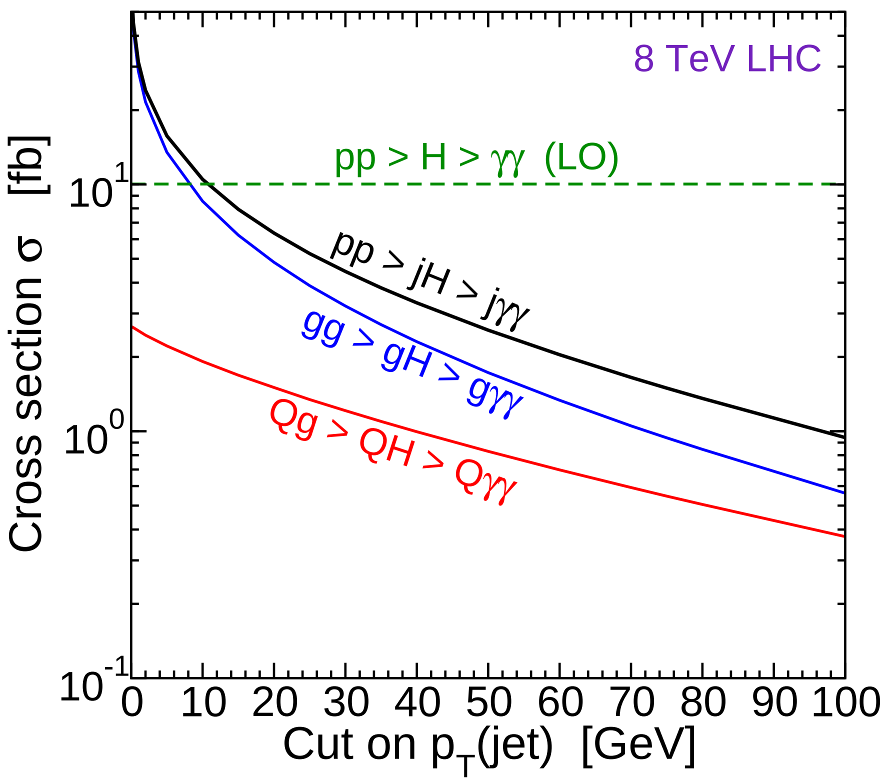
I applied cuts at parton level:

- $p_T(\gamma_1) > 40$ GeV,
- $p_T(\gamma_2) > 30$ GeV,
- $|\eta_\gamma| < 2.5$,
- $\Delta R_{j\gamma} > 0.4$, $\Delta R_{\gamma\gamma} > 0.4$,

There is also a cut on the jet p_T^j, which is varied. A reasonable cut might be $p_T^j > 30$ GeV.

However, it is interesting to consider the formal limit $p_T^j \to 0$, because in that case the result for the mass shift should approach the LO case with no additional jet. This gives a useful check.

Cross-sections for $pp \to jH \to j\gamma\gamma$ and parton-level constituents:

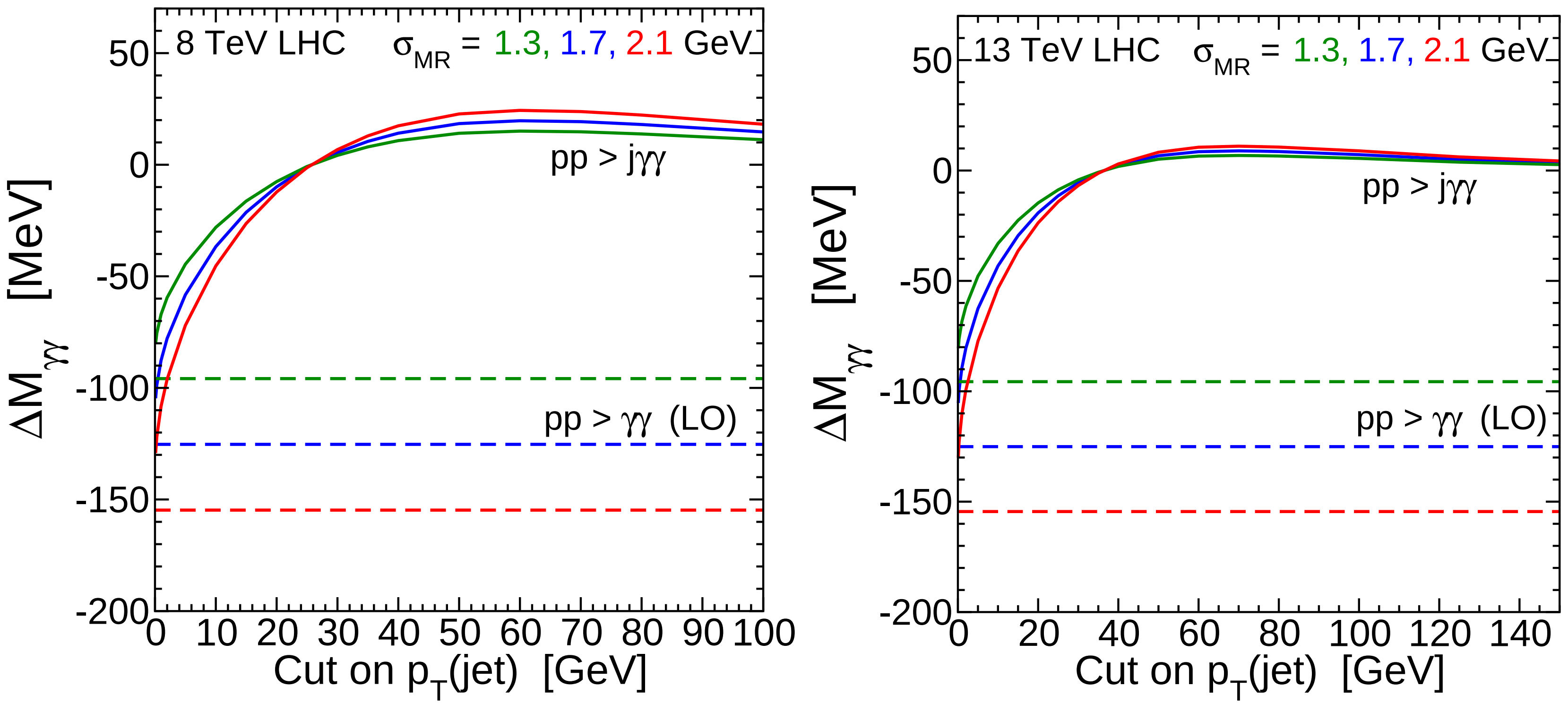


$gg \to g\gamma\gamma$ has $\Delta M_H < 0$

$Qg \to Q\gamma\gamma$ has $\Delta M_H > 0$

Note $gg \to g\gamma\gamma$ diverges for jet p_T cut going to 0, as expected, due to soft and collinear gluon emission. Needs resummation for small jet p_T cut. Divergence cancels against virtual corrections.

Diphoton mass peak shift, for $pp \to j\gamma\gamma$, as a function of the cut on p_T^j:



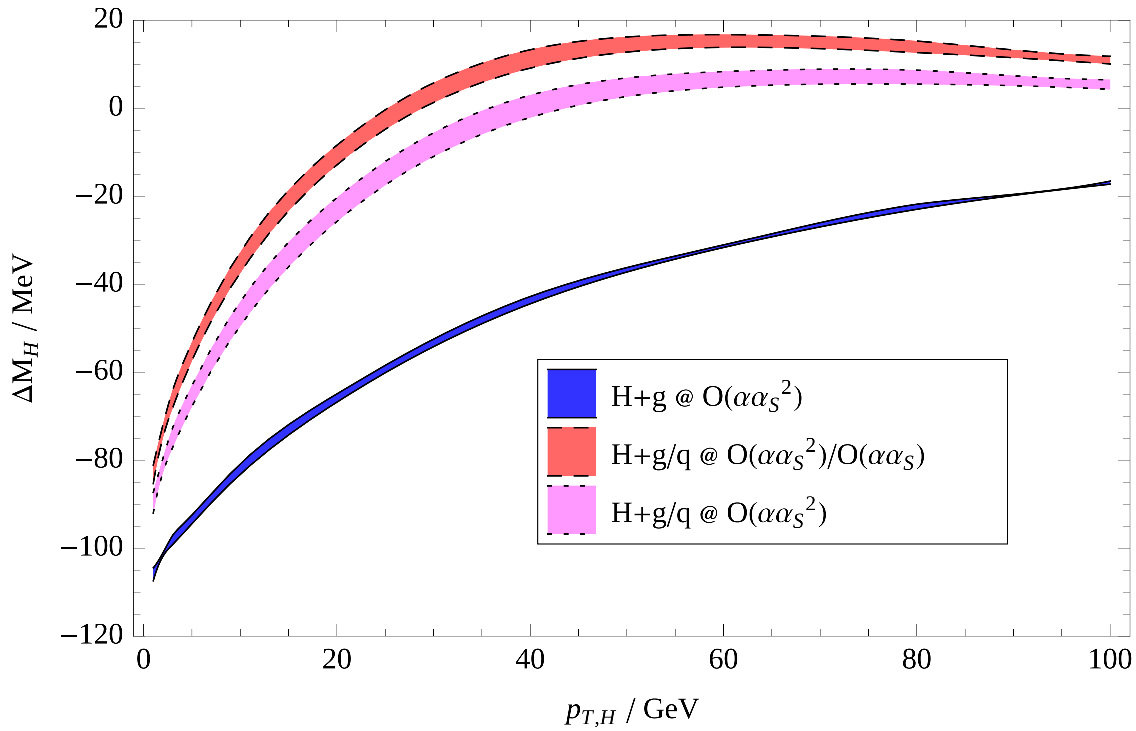
Very small, and positive shift for any reasonable cut on p_T^j.

In formal limit of a small p_T^j cut, mass shift approaches the LO value.

Recently, L. Dixon and Y. Li, 1305.3854 have performed a full NLO calculation, including the virtual 2-loop $gg \to \gamma\gamma$ continuum amplitude and handling soft and collinear divergences from the real radiation using dipole subtraction.

They find an inclusive mass shift ΔM_H of about -70 MeV at NLO.

As a function of the Higgs diphoton p_T (magenta is NLO):



The sharp dependence on p_T could be useful, as it allows observation of the mass shift ΔM_H in $\gamma\gamma$ events alone.

Events with large Higgs p_T, and vector boson fusion events with $H \to \gamma\gamma$ will see almost no mass shift.

Events with small Higgs p_T will see the largest mass shifts.

This avoids the different systematics for mass determination in $ZZ^* \to 4l$.

L. Dixon and Y. Li, 1305.3854: the diphoton mass shift can be used to directly constrain the Higgs width Γ_H.

Otherwise difficult to do in model-independent way at LHC. Present limit from CMS-PAS-HIG-13-016 is $\Gamma_H < 6.9$ GeV.

Beyond the Standard Model:

$$-\mathcal{L}_{\rm eff} = H\left(c_g f_g^{\rm SM} \alpha_S G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma f_\gamma^{\rm SM} \alpha F_{\mu\nu} F^{\mu\nu}\right)$$

Signal strength:

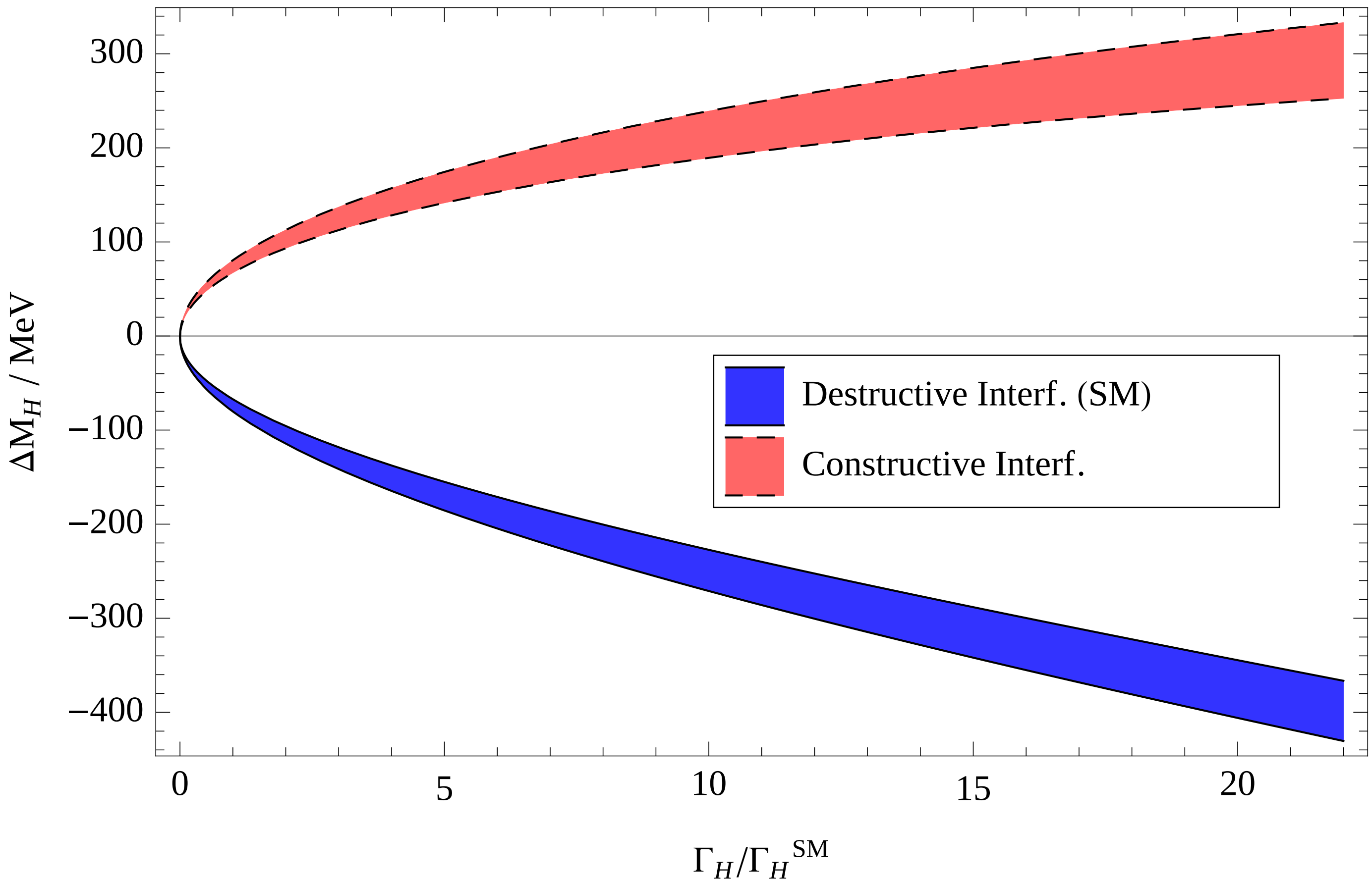
$$\sigma_{pp\to H\to\gamma\gamma} \propto \frac{(c_g c_\gamma)^2}{\Gamma_H} + \ldots$$

But the mass shift in diphoton events goes like:

$$\Delta M_H \propto c_g c_\gamma + \ldots$$

So measuring both can give a direct limit, or maybe even a measurement, of Γ_H.

L. Dixon and Y. Li, 1305.3854: relation between ΔM_H and Γ_H, assuming that $\sigma(pp \to H \to \gamma\gamma)$ is close to the Standard Model value:



Outlook

- Interference with background shifts the position of the Higgs diphoton mass peak by about -70 MeV (Dixon and Li, NLO). Not huge, but probably significant compared to the eventual uncertainty, and to the last significant digit being reported even today. The LO prediction was about -120 MeV.
- Sharp dependence on the Higgs p_T may allow observation of the mass shift entirely in diphoton samples.
- Requiring an additional central jet, the shift is very small: -10 to $+10$ MeV.
- The VBF diphoton and $ZZ^* \to 4l$ Higgs mass determinations should be nearly unaffected by interference with background.
- A direct upper bound on Γ_H (of order few tens $\times \Gamma_H^{\rm SM}$) should already be possible.
- NNLO calculation?