Bounding the Higgs width at the HL-LHC

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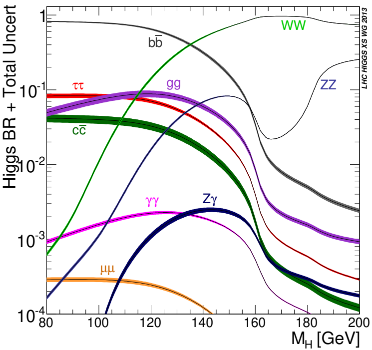
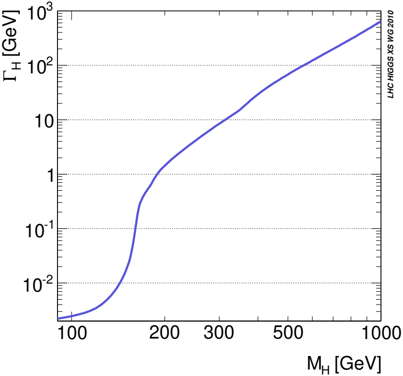
Introduction

[HXSWG] arXiv:1101.0593, arXiv:1201.3084

- Width of a resonance is determined by mass & interactions
  [http://pdg.lbl.gov]
  $$\Gamma = \int \frac{(2\pi)^4}{2M} |\mathcal{A}|^2 d\Phi_n(P; p_1, \ldots, p_n) \xrightarrow{n=2} \frac{1}{32\pi^2} |\mathcal{A}|^2 \frac{|\vec{p}_1|}{M^2} \int d\Omega_2$$
  2-particle decay width a constant as $|\vec{p}_1| = \sqrt{(M^2 - m_1^2 - m_2^2) - 4m_1^2 m_2^2} \,/\, 2M$
- Calculated SM Higgs width at m_H=125 GeV $\rightarrow \Gamma_{H,SM} \approx$ 4 MeV



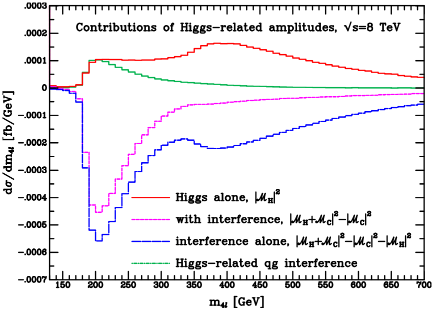


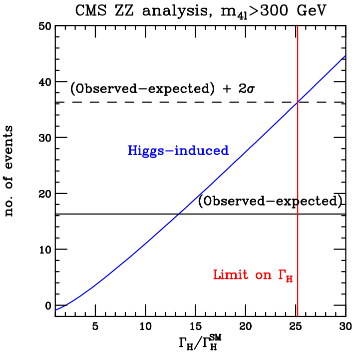
[Caola,Melnikov] arXiv:1307.4935, [Campbell,Ellis,Williams] arXiv:1311.3589

- Cross section in $i \to H \to f$ in the narrow-width approximation

$$\frac{d\sigma_{pp\to H\to f}}{dM_f^2} \propto \frac{g_i^2 g_f^2}{(M_f^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \xrightarrow{\text{NWA}} \frac{g_i^2 g_f^2}{\Gamma_H/\pi}$$

- In $gg \to H \to ZZ \to 4l$ the off-peak cross section is large
  Given on-peak NWA cross section, can use off-peak rate to bound Γ_H
- Could be invalidated by form factors [Englert,Spannowsky] arXiv:1405.0285



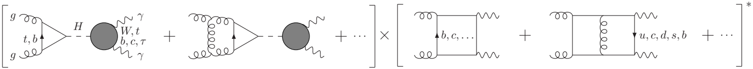


Bounding the width – Resonance region

- Signal-background interference in $gg(\to H) \to \gamma\gamma$
  [Dicus,Willenbrock] PRD37(1988)1801, [Dixon,Siu] hep-ph/0302233

$$\mathcal{M}_{gg\to\gamma\gamma} = \frac{\mathcal{A}_S/\sqrt{\pi}}{m_{\gamma\gamma}^2 - m_H^2 + i m_H \Gamma_H} + \frac{\mathcal{A}_B}{\sqrt{\pi}}$$

- Change in cross section from interference effect proportional to



$$= 2\,\frac{m_{\gamma\gamma}^2 - m_H^2}{\pi}\,\frac{\mathrm{Re}\left\{\mathcal{A}_S\mathcal{A}_B^*\right\}}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2} + 2\,\frac{m_H\Gamma_H}{\pi}\,\frac{\mathrm{Im}\left\{\mathcal{A}_S\mathcal{A}_B^*\right\}}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

- Real part asymmetric around peak, and imaginary part symmetric
- How can this be made measurable?

The measurable line shape

[Martin] arXiv:1208.1533, arXiv:1303.3342, [deFlorian et al.] arXiv:1303.1397

- Line shape is measured only after convolution with the detector resolution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}} = \sum_{a,b=q,g} \int \mathrm{d}m^2 \, \frac{\mathrm{d}L_{ab}(m^2/s)}{\mathrm{d}m^2} \, \hat{\sigma}_{ab}(m) \, \mathcal{D}(m, m_{\gamma\gamma})$$

where $L_{ab}(\tau) \to$ parton luminosity, $\hat{\sigma}_{ab}(m) = \int \mathrm{d}\Phi |\mathcal{M}_{ab}|^2/(2m^2)$, and

$$\mathcal{D}(m, m_{\gamma\gamma}) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(m-m_{\gamma\gamma})^2}{2\,\sigma^2}} \qquad \to \qquad \text{Detector model}$$

- Define signal and real/imaginary part of interference as

$$\hat{\sigma}_{\mathrm{S}} = \mathrm{Re}\left\{\frac{\mathcal{L}}{M_H}\right\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi \, \frac{|\mathcal{A}_S|^2}{m_H \Gamma_H} \,,$$

$$\hat{\sigma}_{\mathrm{I/R}} = \mathrm{Re/Im}\left\{\frac{\mathcal{L}}{M_H}\right\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi \, 2\,\mathrm{Im/Re}\{\mathcal{A}_S \mathcal{A}_B^*\}$$

where the line shape is given by the complex Lorentzian

$$\mathcal{L} = \frac{iM_H/\pi}{m_{\gamma\gamma}^2 - M_H^2} \,, \qquad M_H = \sqrt{m_H^2 - i\,m_H \Gamma_H}$$

The measurable line shape

[Bothmann,Dixon,Kuttimalai,SH] TBP

- Parton luminosity and matrix element approximately constant around m_H
- Measurable line shape to good accuracy given by convolution integral

$$\mathcal{S} = \int_{-\infty}^{\infty} \mathcal{L}(\bar{m})\mathcal{D}(m-\bar{m})\mathrm{d}\bar{m} = \frac{iM_H}{\sqrt{2\pi^3}\sigma}\int_{-\infty}^{\infty} \frac{e^{-\frac{(m-\bar{m})^2}{2\sigma^2}}}{\bar{m}^2 - M_H^2}\mathrm{d}\bar{m}$$

- Can be expressed in terms of Faddeeva function $w(z) = e^{-z^2}\mathrm{erfc(iz)}$

$$\mathcal{S} = \frac{w(z_-) - w(z_+)}{2\sqrt{2\pi}\,\sigma}\;, \qquad z_\mp = \frac{m_{\gamma\gamma} \mp M_H}{\sqrt{2}\,\sigma}$$

- Complete line profile of Higgs boson signal plus interference

$$\mathcal{F} = N_R\,\frac{\mathrm{Re}\{\mathcal{S}\}}{\mathrm{Re}\{\mathcal{N}\}} + N_I\,\frac{\mathrm{Im}\{\mathcal{S}\}}{\mathrm{Im}\{\mathcal{N}\}}\;,$$

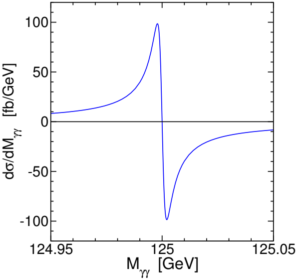
$\mathcal{N} \to$ Normalization of $\mathcal{S}$

- In the Standard Model, N_R and N_I determined by

$$N_R = \frac{\sigma_S}{\Gamma_H} + \sigma_I\;, \qquad N_I = \sigma_R\;, \qquad \sigma_{S,I,R} = \int_0^{m_H} \mathrm{d}m_{\gamma\gamma}\,\frac{\mathrm{d}\sigma_{\mathrm{S,I,R}}}{\mathrm{d}m_{\gamma\gamma}}$$

The measurable line shape

- Effect of the convolution at LO [Martin] arXiv:1208.1533, arXiv:1303.3342



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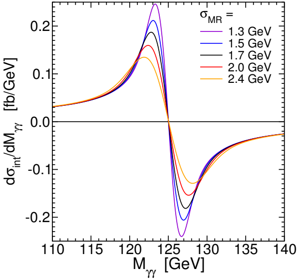
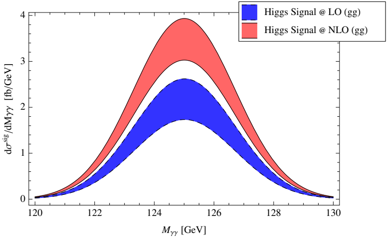
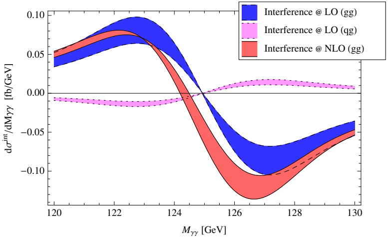


- Size of NLO corrections [Dixon,Li] arXiv:1305.3854, [deFlorian et al.] arXiv:1303.1397





Parametrizing new physics effects

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- Effective coupling of Higgs to gluons & photons

$$\mathcal{L} = -\left[\frac{\alpha_s}{8\pi} c_g b_g G^a_{\mu\nu} G_a^{\mu\nu} + \frac{\alpha}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \frac{h}{v} \qquad b_g = \frac{2}{3},\ b_\gamma = \frac{47}{9} \quad \text{at LO}$$

$c_{g/\gamma}$ – new physics correction factors

- In narrow width approximation

$$\sigma_{gg\to H\to\gamma\gamma} \propto \int \mathrm{d}m^2_{\gamma\gamma}\, \frac{|\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}|^2}{(m^2_{\gamma\gamma} - m^2_H)^2 + m^2_H \Gamma^2_H} \propto \frac{c_g^2 c_\gamma^2}{\Gamma_H}$$

- On-peak measurements invariant under simultaneous scaling

$$c_{g/\gamma} \to \xi c_{g/\gamma}\ , \qquad \Gamma_H \to \xi^4 \Gamma_H$$

- Interference effects break degeneracy as N_I scales different than N_R

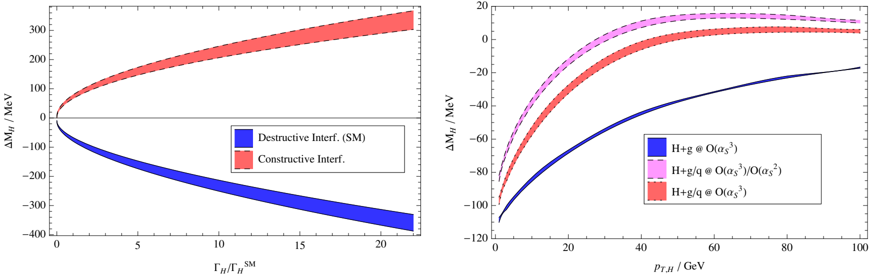
$$c_g c_\gamma \approx \sqrt{\Gamma_H / \Gamma_H^{SM}}$$

- Allows to bound Higgs width using on-peak data alone
  - Measure apparent mass shift [Dixon,Li] arXiv:1305.3854
  - Directly fit for line shape [Bothmann,Dixon,Kuttimalai,SH] TBP

The mass shift method

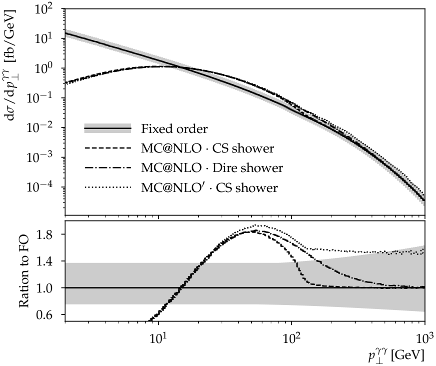
[Dixon,Li] arXiv:1305.3854

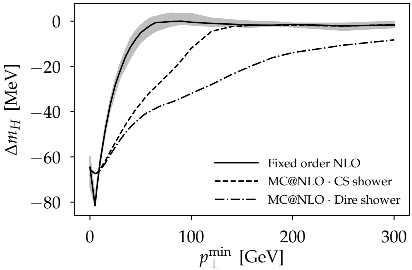
- Asymmetric form of $\mathrm{Im}\{\mathcal{F}\}$ creates apparent shift of Higgs mass peak $m_H \to \tilde{m}_H = m_H + \Delta m_H$, but need reference mass to measure effect
  - $h \to ZZ \to 4l$ (different calibration)
  - VBF-enriched $h \to \gamma\gamma$ [Coradeschi et al.] arXiv:1504.05215
- At NLO QCD strong dependence of Δm_H on $p_{T,H}$
  $\to$ measure reference mass by analyzing $\gamma\gamma$ channel in two $p_{T,H}$ bins?



The p_T dependent mass shift method

- p_T spectrum in low-p_T region cannot be determined reliably at fixed order QCD
- Analytic NLL result derived in [Cieri, Coradeschi,deFlorian,Fidanza] arXiv:1706.07331

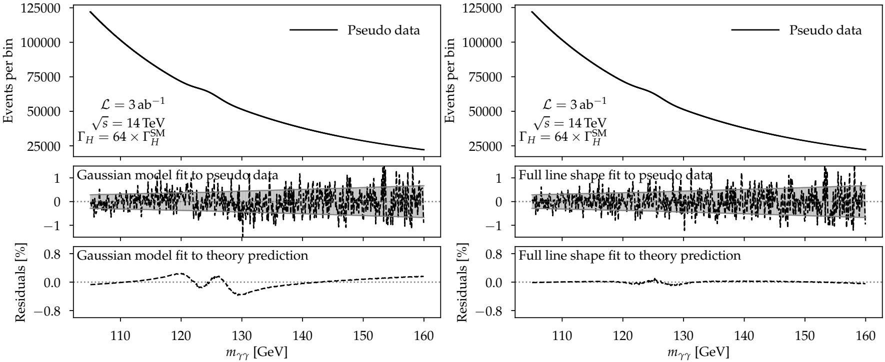




- Parton-shower matching performed to two different shower algorithms [Bothmann,Dixon,Kuttimalai,SH] TBP
- Large uncertainties [Nason,Webber] arXiv:1202.1251 related to universal large higher-order corrections [Magnea,Sterman] PRD42(1990)4222

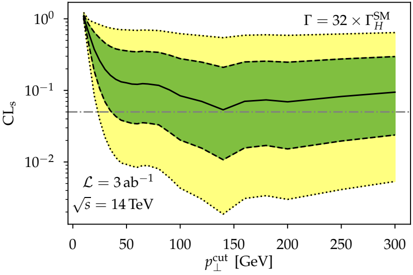
The direct fit method

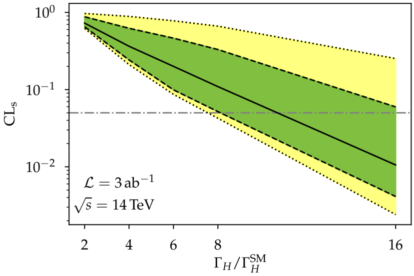
- Comparison between fit to Gaussian and to SM line shape $\mathcal{F}$ overlayed on continuum background $(N\exp\{-Am_{\gamma\gamma} - Bm_{\gamma\gamma}^2 - Cm_{\gamma\gamma}^3\})$
- Significantly smaller residuals when fitting with correct shape
  Makes use of all experimental data in fiducial region
- Clearly depends on featureless background around m_H
  Will suffer from possible asymmetric detector effects (ideas?)



[Bothmann,Dixon,Kuttimalai,SH] TBP

- Analysis assumes integrated luminosity of $3ab^{-1}$
- Toy experiments, x-checked with approximate error estimate [Cowan] priv.comm





- p_T based method
- Direct fit method

Summary

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- Interference effects allow to bound Higgs width well below experimental resolution in a fairly model independent way
- $\gamma\gamma$ channel shows large effect while working close to resonance mass
- p_T dependent method suffers from large uncertainties as slicing cut lies in region affected by matching of NLL-resummed spectrum to fixed-order calculation $\rightarrow$ no theory guidance
- Direct fit method may suffer from distortions of peak shape arising from non-Gaussian / asymmetric detector effects
- Any input / advice / recommendations welcome