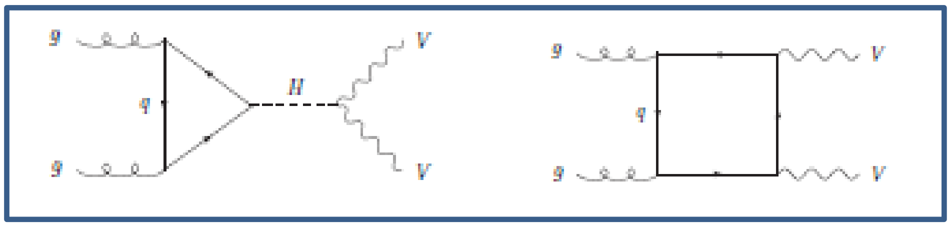
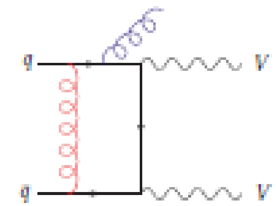
Higgs interference overview

(borrowing from slides of Daniel de Florian, Sara Bolognesi and Sara Diglio)

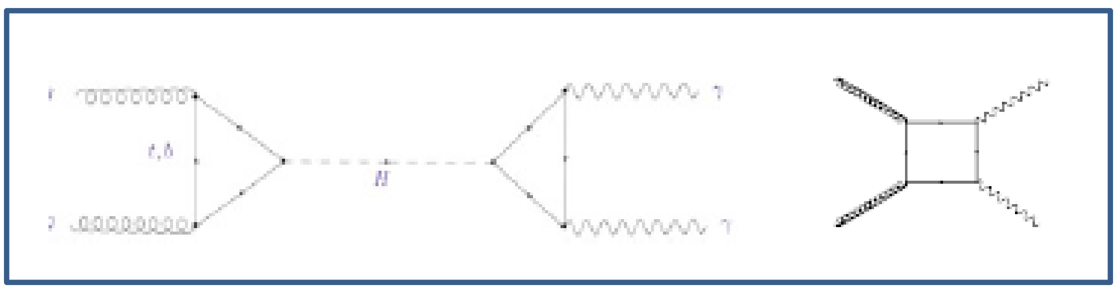
gg Higgs signal and irred. background

gg → H → WW/ZZ





gg → H → γγ



Similarly: VBF and other Higgs production channels

Activity

Higgs-continuum $gg \rightarrow VV$ interference Glover, van der Bij (1989); Binoth, Ciccolini, NK, Krämer (2006) (gg2WW); Campbell, Ellis, Williams (2011) (MCFM); NK (2012) (gg2VV); Passarino (2012); NK, Passarino (2012); Campanario, Li, Rauch, Spira (2012); Frixione, Hirschi, Laureys, Maltoni (aMC@NLO); Bonvini, Caola, Forte, Melnikov, Ridolfi (2013) approx. (N)NLO

Higgs-continuum $gg \rightarrow \gamma\gamma$ and $\gamma\gamma j$ interference Dicus, Willenbrock (1988); Dixon, Siu (2003); Martin (2012, 2013); de Florian et al. (2013); Dixon, Li (2013) NLO

plus VBF (VBFNLO group & Phantom group)

and experimental studies in ATLAS and CMS

EXP-TH collaboration in LHC Higgs Cross Section Working Group

Mass peak shift in H → γ γ

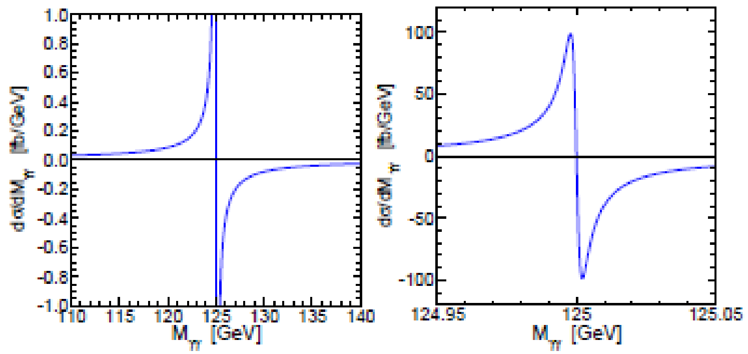


FIG. 1: The distribution of diphoton invariant masses from the real interference term in eq. (12), as a function of $M_{\gamma\gamma} = \sqrt{\hat{s}}$, from eq. (10), before including experimental resolution effects. The right panel is a close-up of the left panel, showing the maximum and minimum near $M_{\gamma\gamma} = M_H \pm \Gamma_H/2$.

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- small asymmetry in the interference
- at this level shift is O(MeV) as expected

Asymmetry enhanced by detector resolution can reach 100 MeV effect

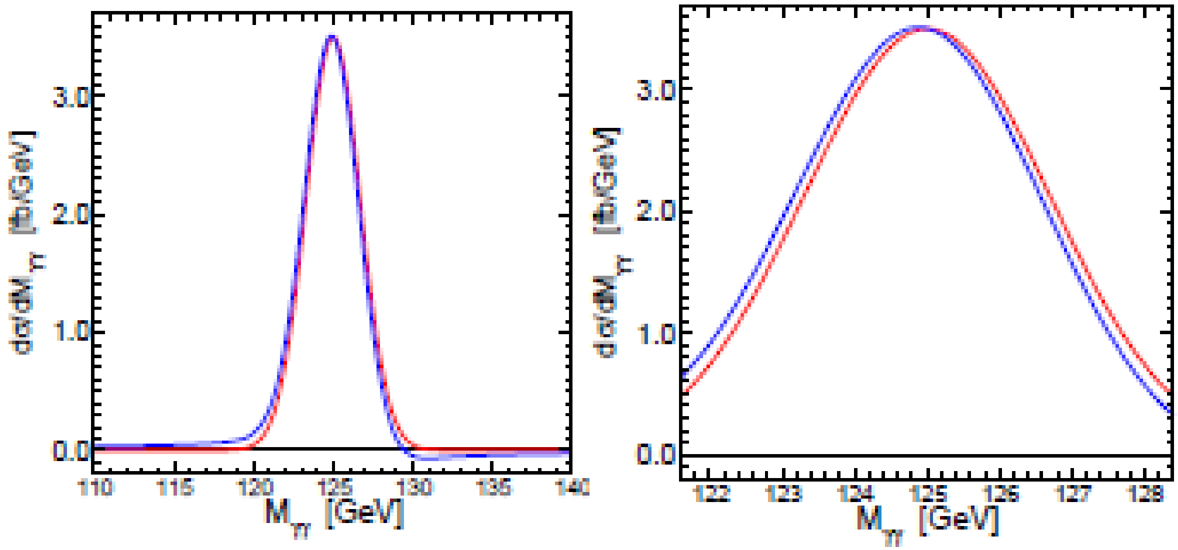
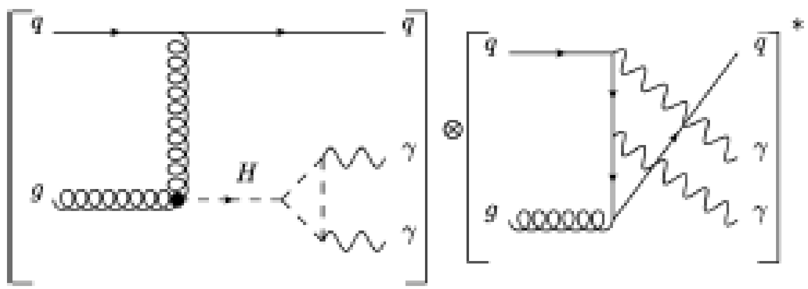


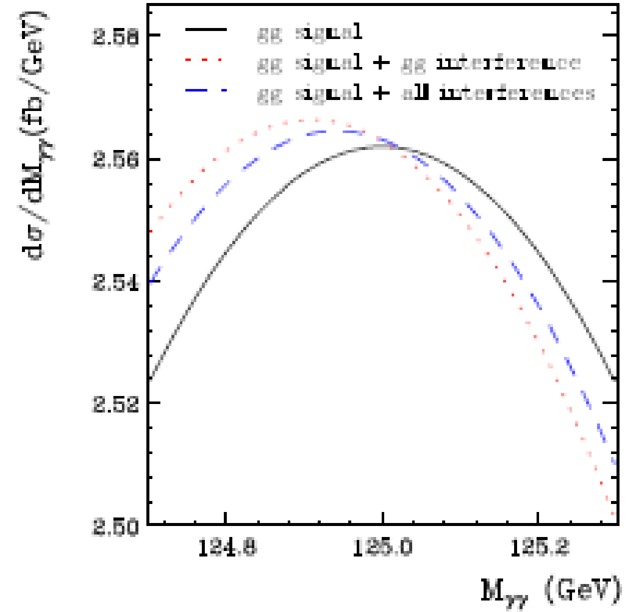
FIG. 3: Diphoton invariant mass distributions with a Gaussian mass resolution of width $\sigma_{MR} = 1.7$ GeV. In each panel, the right (red) curve includes only the Higgs contribution without interference, and the left (blue) curve also includes the interference contribution from Figure 2. The right panel is a close-up of the left panel.

Effects from other channels go in opposite direction

- D.deF., N.Fidanza, R.Hernandez-Pinto, J.Mazzitelli, Y.Rotstein, G.Sborlini



90 MeV ⟶ 60 MeV



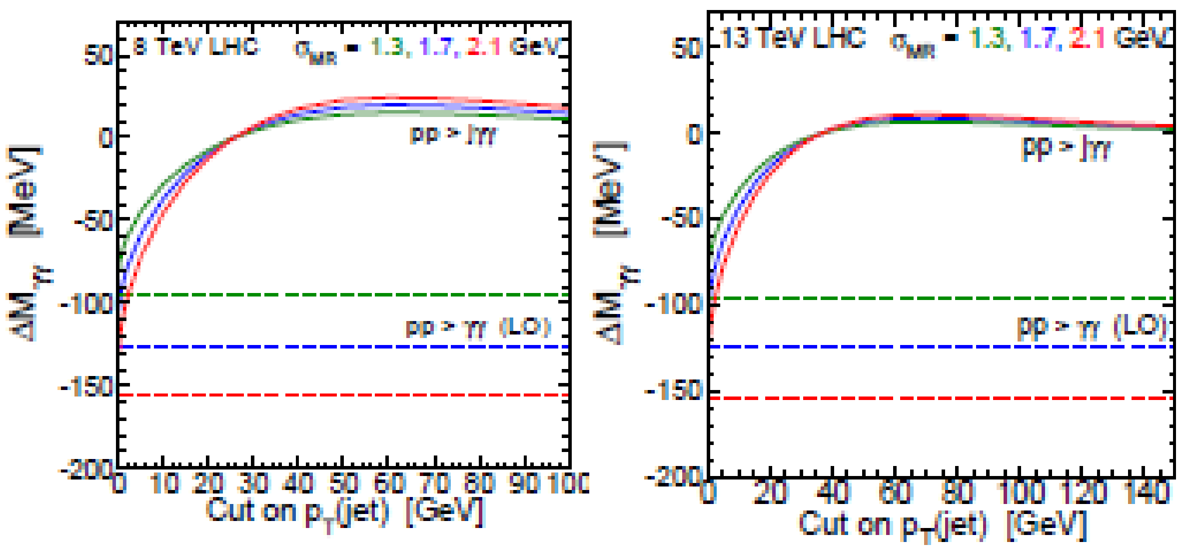


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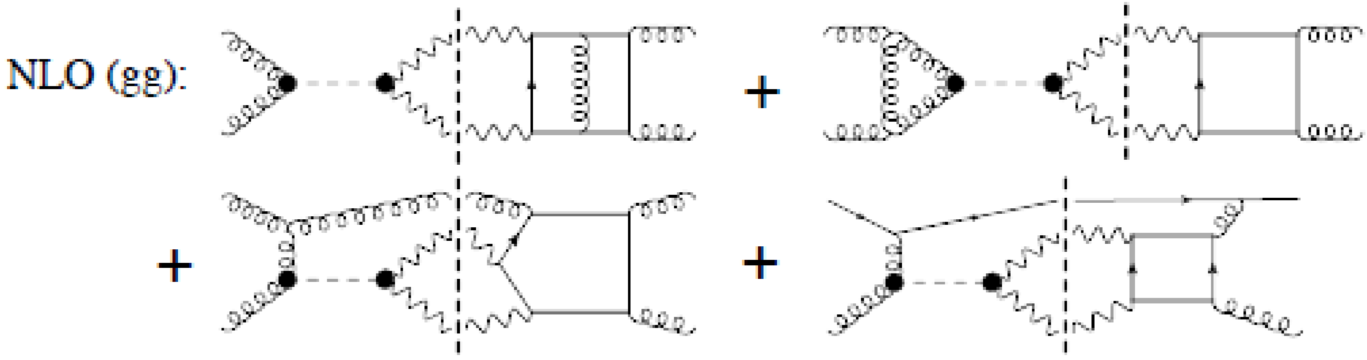
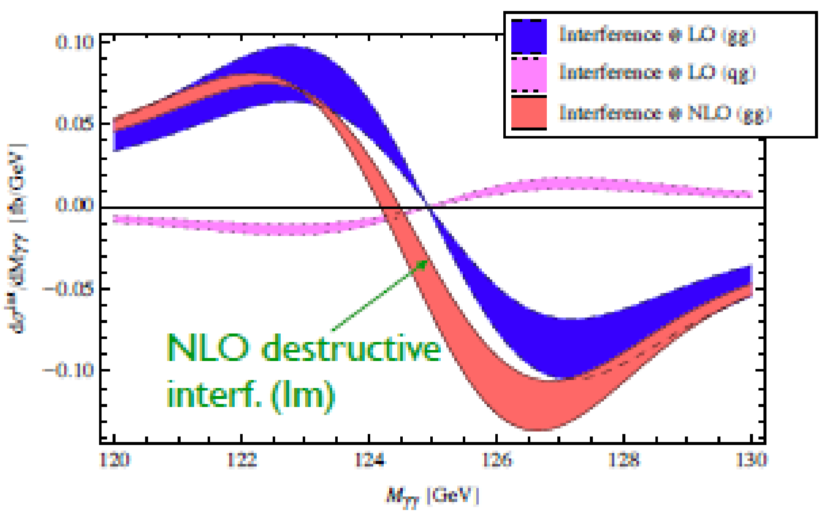
FIG. 4.3: The solid lines show the shifts in the diphoton mass peak, $\Delta M_{\gamma\gamma} \equiv M_{\gamma\gamma}^{\rm peak} - M_H$, for $pp \to j\gamma\gamma$, as a function of the cut on the transverse momentum of the jet, $p_{T,\rm cut}^{j}$, with other cuts as described in the text, for $\sigma_{MR} = 1.3$, 1.7, and 2.1 GeV (from top to bottom on the left). The dashed lines shows the results for $pp \to \gamma\gamma$ at leading order without a jet requirement, again for $\sigma_{MR} = 1.3$, 1.7, and 2.1 GeV (from top to bottom). The left panel is for pp collisions with $\sqrt{s} = 8$ TeV, and the right panel for $\sqrt{s} = 13$ TeV.

Interference at NLO

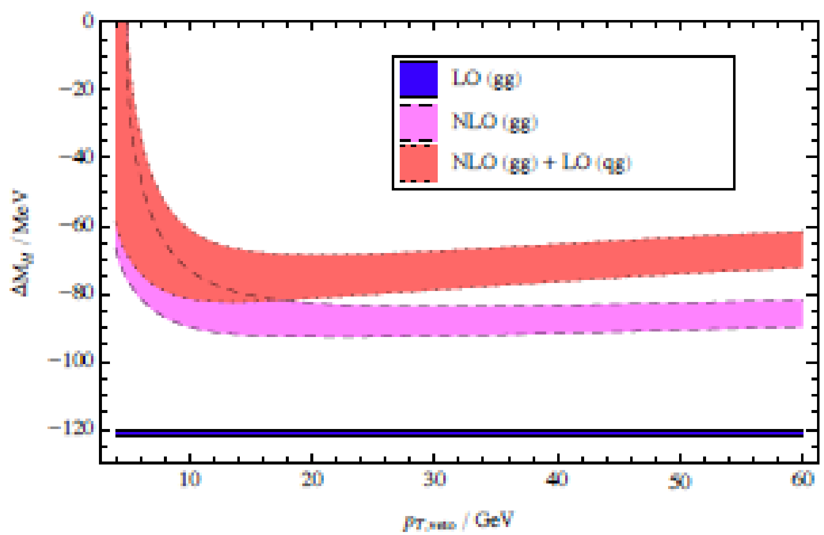
L.Dixon, Y.Li (2013)



Interferences



Mass shift



Reduction in mass shift but sensitive to width

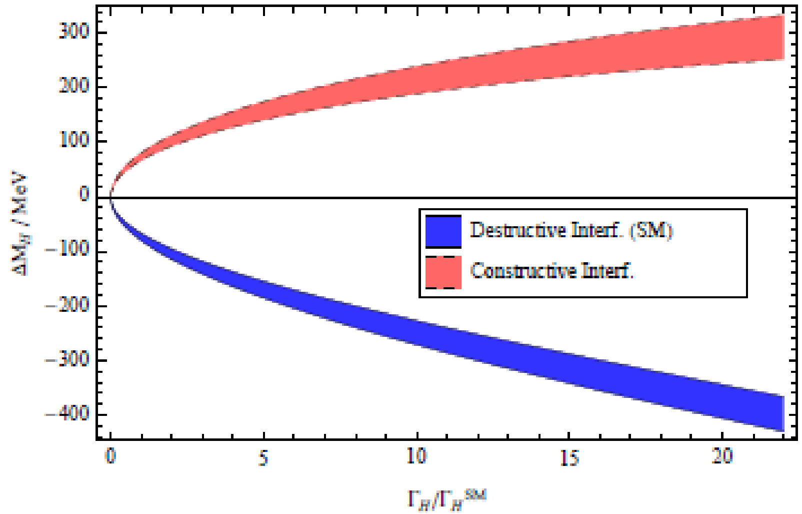
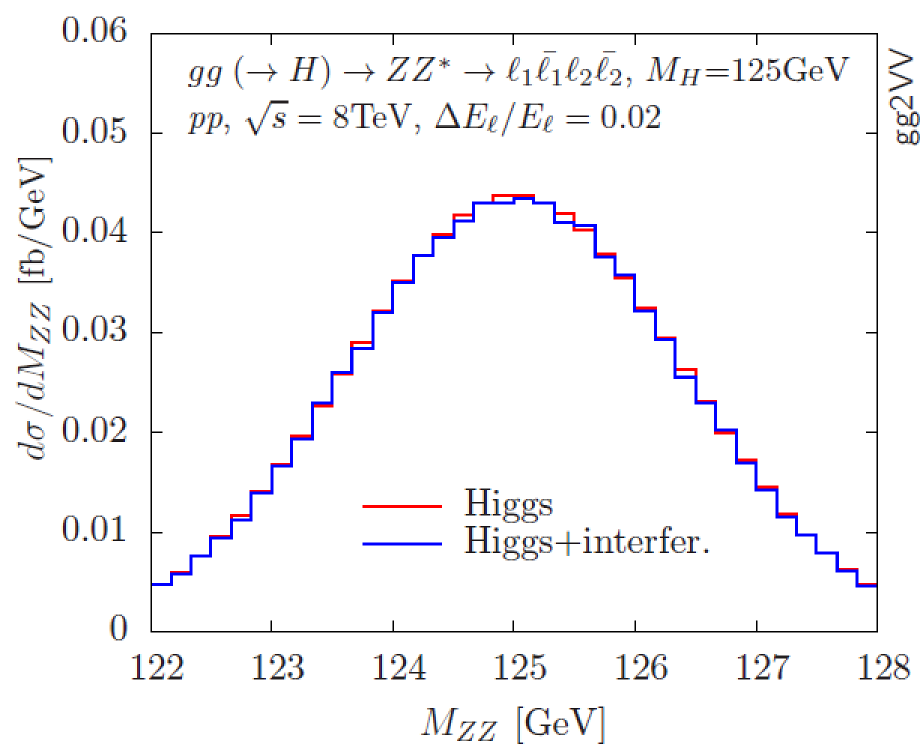


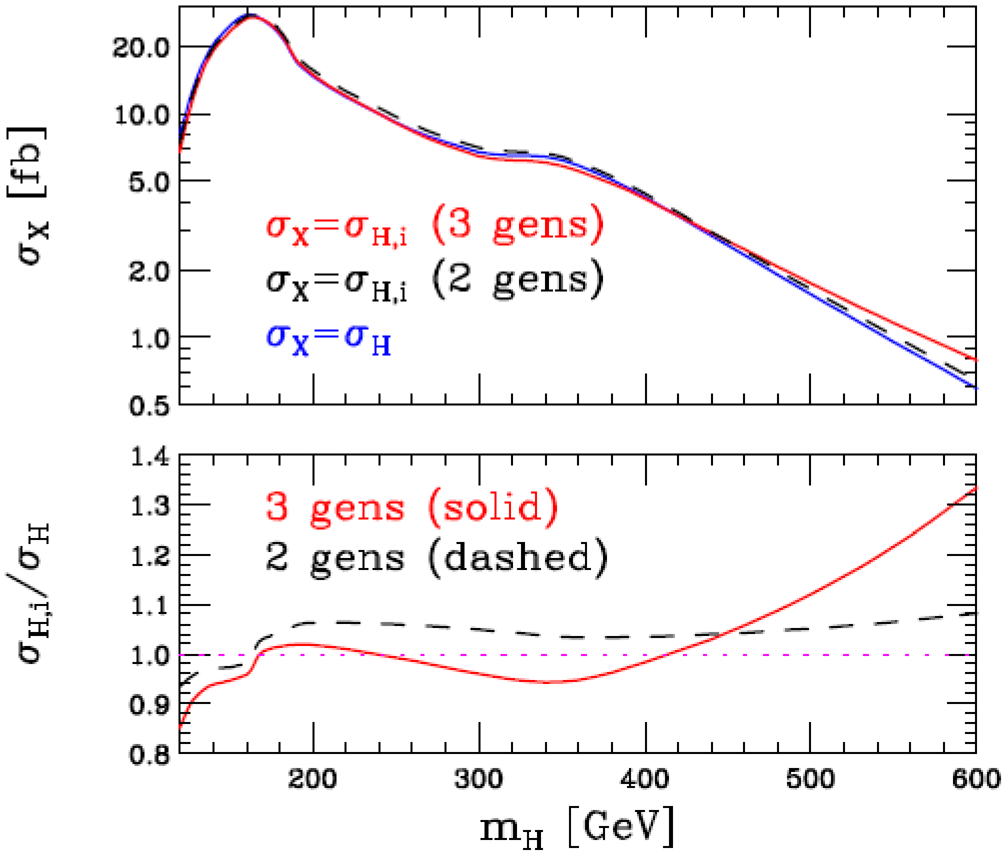
FIG. 5. Higgs mass shift as a function of the Higgs width. The coupling $c_{g\gamma}$ has been adjusted to maintain a constant signal yield.

H→ γ γ peak shift dependence on width

H→ ZZ peak shift is tiny



gg → H → WW (light & heavy H)



Campbell, Ellis, Williams

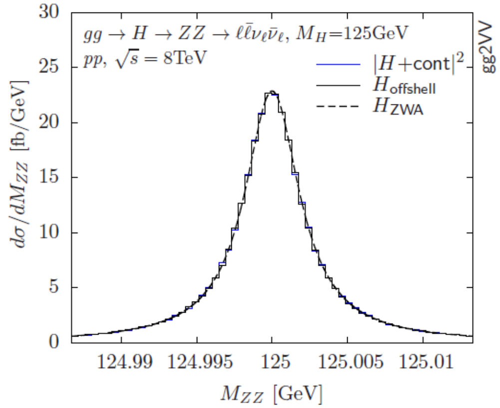
MCFM

Figure 6: Upper panel: The cross sections for $gg \to H \to W^+(\to \nu_e e^+)W^-(\to \mu^- \bar{\nu}_\mu)$ in femtobarns, with ($\sigma_{H,i}$) and without (σ_H) the interference with SM $gg \to WW$ production. The dashed line represents the calculation of $\sigma_{H,i}$ including only the first two generations of quarks. Lower panel: The ratio of the cross sections with and without the interference terms. The dotted magenta line highlights the boundary between constructive and destructive interference.

gg → H → VV: light Higgs (M_H=126 GeV)

Decay modes, where Higgs mass can be reconstructed:

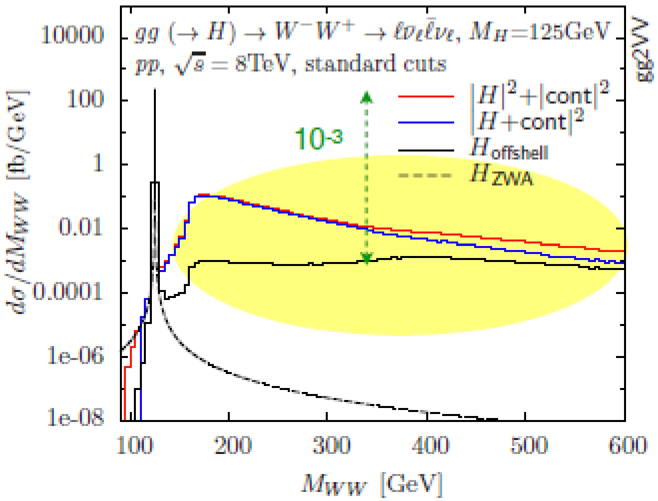
Cuts select resonance region, where interference effects are negligible



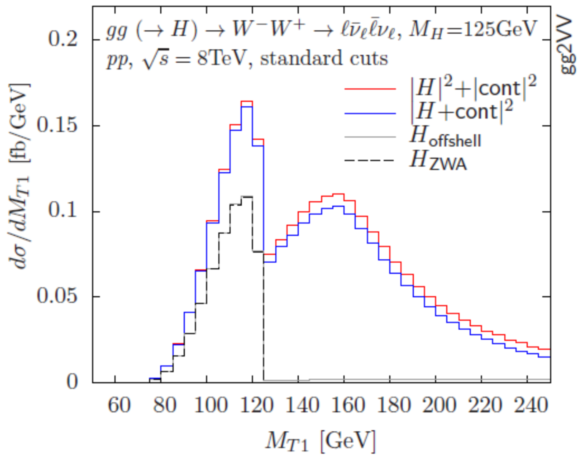
Decay modes, where Higgs mass cannot be reconstructed:

a priori: large interference effects, O(10%)

Can Higgs tail be observed??

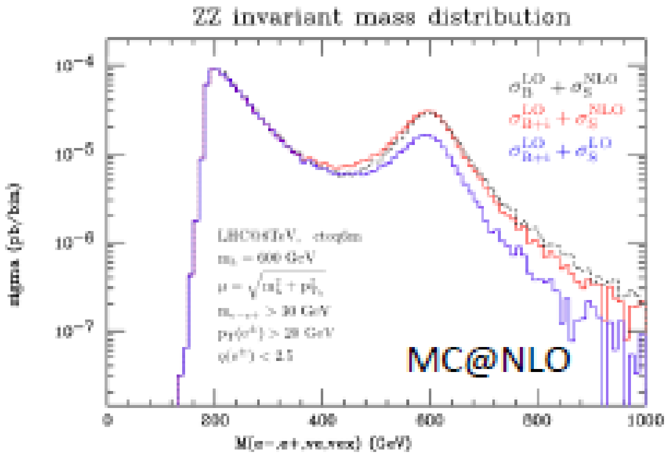


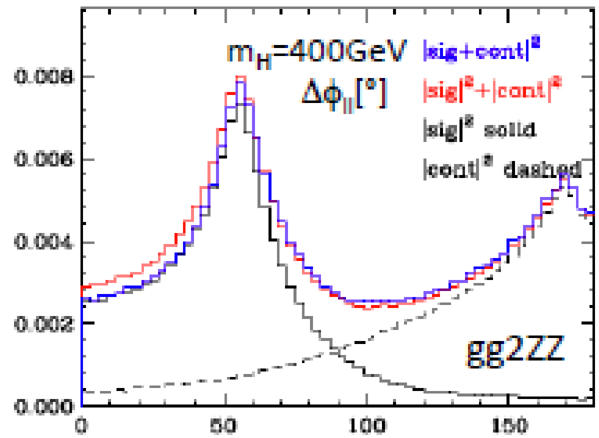
strongly reduce problematic tail with M_T cut (MCFM):



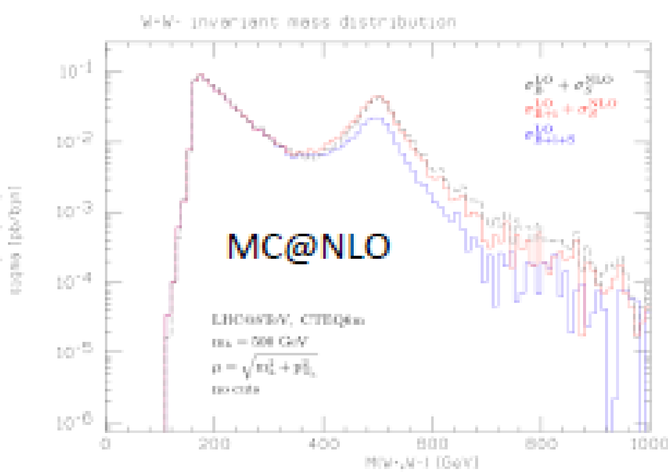
Integration over large kinematical range enhances off-shell effects and interference with background

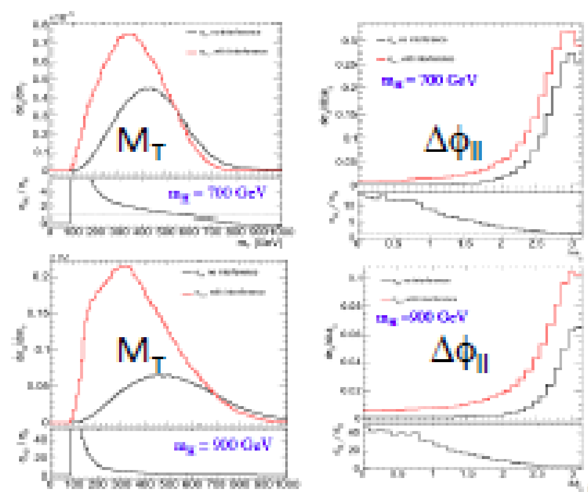
INTERFERENCE EFFECTS IN GG→VV –REMINDER-





H→ZZ





MCFM
Lashkar Kashif

H→WW

MC STATUS FOR GGF: CPS AND INTERFERENCE

- PowHeg BOX
  - NLO event generator
  - CPS propagator – NO Interference
- gg2VV 3.1.1
  - parton level event generator
  - gg→WW→ lνlν and ZZ→4l/2l2ν interference calculation at **LO: S+I+B**
  - same final state interference between WW→ lνlν and ZZ→2l2ν
  - Soon gg → WW→ lνqq and gg → ZZ→ llqq
  - CPS propagator
- MC@NLO v4.09
  - parton level event generator (signal at NLO)
  - gg → WW→ lνlν and ZZ→4l/2l2ν interference calculation: **B+I (LO-Madgraph based) + S(NLO)**
  - CPS propagator

Event generators with LHE format output that can be interfaced with Parton Shower

- MCFM 6.3
  - parton level MC code
  - gg→WW→ lνlν interference calculation at **LO: S+I**

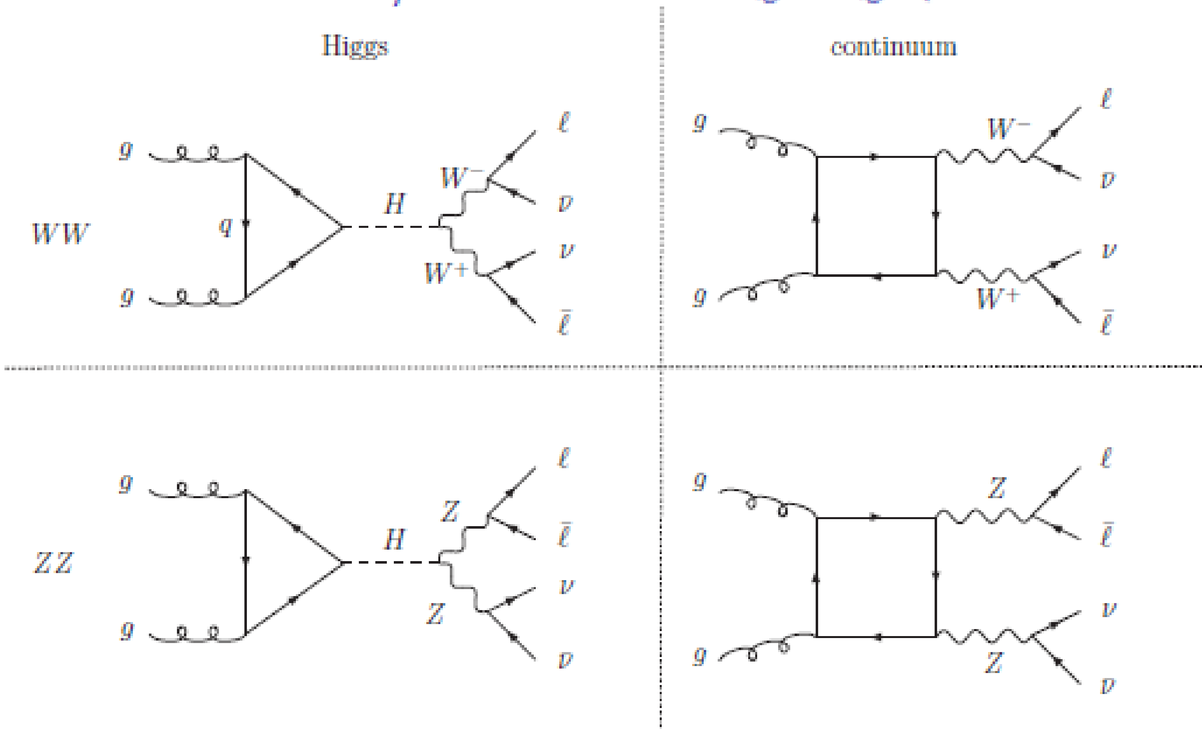
MC STATUS FOR VBF: PROPAGATOR AND INTERFERENCE

- PowHeg BOX
  - NO s/b Interference
  - CPS propagator
- VBF@NLO
  - s/b interference at LO
  - full ME pp->jj4l
- Phantom
  - s/b interference at LO
  - full ME pp->jj4l

Event generators with LHE format output that can be interfaced with Parton Shower

- HAWK
  - NO s/b interference
  - NO matching to PS
  - NLO QCD and EW corrections

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ (same flavour)



same flavour: all four contributions interfere (different flavour: WW only)

continuum WW/ZZ interference:

Nason and Rocket team studied continuum WW/ZZ interference in quark scattering (LO) $\to$ negligible (arXiv:1107.5051)

$gg \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ with minimal cuts: negative interference of $\sim 6\%$ at 8 TeV

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ (same flavour) at $M_H = 125$ GeV

Due to H → WW search cuts: ZZ contribution does not affect interference effects much

Heavy Higgs analysis

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$: $H \to ZZ$ search cuts

process	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV			interference	
	H_{offshell}	cont	$\lvert H_{\text{ofs}}+\text{cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to ZZ$	0.2175(8)	0.0834(2)	0.3150(8)	1.047(4)	1.065(6)
$gg\ (\to H) \to WW/ZZ$	0.2220(8)	0.1020(2)	0.3406(8)	1.051(4)	1.075(6)

process	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV			interference	
	H_{offshell}	cont	$\lvert H_{\text{ofs}}+\text{cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to ZZ$	0.01265(5)	0.0687(2)	0.0927(2)	1.140(3)	1.90(2)
$gg\ (\to H) \to WW/ZZ$	0.01278(5)	0.0846(3)	0.1090(2)	1.119(3)	1.91(3)

$H \to ZZ$ search cuts: $|M_{\ell\bar{\ell}} - M_Z| < 15$ GeV, $\not{E}_T > 110$ GeV, $M_T > 325$ GeV

$M_T = \sqrt{(M_{T,\ell\ell} + \not{M}_T)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2}$ with $\not{M}_T = \sqrt{\not{p}_T^2 + M_{\ell\ell}^2}$, other as above

$$R_1 := \frac{\sigma(|\mathcal{M}_\text{H} + \mathcal{M}_\text{cont}|^2)}{\sigma(|\mathcal{M}_\text{H}|^2) + \sigma(|\mathcal{M}_\text{cont}|^2)} \qquad R_2 := \frac{\sigma(|\mathcal{M}_\text{H}|^2 + 2\,\text{Re}(\mathcal{M}_\text{H}\mathcal{M}^*_\text{cont}))}{\sigma(|\mathcal{M}_\text{H}|^2)}$$

Heavy Higgs analysis

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$: $H \to WW$ search cuts

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	0.3124(3)	0.07607(7)	0.3988(4)	1.027(2)	1.033(2)
$gg\ (\to H) \to WW/ZZ$	0.4460(5)	0.09851(8)	0.5715(6)	1.050(2)	1.060(2)

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	0.01287(2)	0.008383(8)	0.02369(2)	1.115(2)	1.189(2)
$gg\ (\to H) \to WW/ZZ$	0.01949(2)	0.01265(2)	0.03824(4)	1.190(2)	1.313(3)

$H \to WW$ search cuts: $p_{T\ell} > 40$ GeV, $|\eta_\ell| < 2.5$, $\not{E}_T > 25$ GeV,
$M_{\ell\bar{\ell}} > 50$ GeV, $\Delta\eta_{\ell\bar{\ell}} < 1$, $p_T(\ell\bar{\ell}) > 30$ GeV, $0.6M_H < M_T < M_H$

$$M_T = \sqrt{(M_{T,\ell\ell} + \not{p}_T)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2} \text{ with } M_{T,\ell\ell} = \sqrt{p_{T,\ell\ell}^2 + M_{\ell\ell}^2}$$

gg → H → VV: QCD vs. interference corrections

How to combine NNLO signal with LO interference and background?

G.Passarino

Additive

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = \frac{d\sigma^{\rm NNLO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B)$$

Multiplicative

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\,[\frac{d\sigma^{\rm LO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I)] + \frac{d\sigma^{\rm LO}}{dx}(B), \qquad K_{\rm D} = \frac{\frac{d\sigma^{\rm NNLO}}{dx}(S)}{\frac{d\sigma^{\rm LO}}{dx}(S)},$$

Intermediate

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\frac{d\sigma^{\rm LO}}{dx}(S) + (K^{\rm gg}_{\rm D})^{1/2}\frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B)$$

"Central value"

Estimation of associated theoretical uncertainty G. Passarino

New:

Signal-background interference effects for $gg \to H \to W^+W^-$ beyond leading order

see talk by Fabrizio Caola

M.Bonvini, F.Caola, S.Forte, K.Melnikov, G.Ridolfi

Use soft-virtual approximation at NNLO (assuming two-loop Higgs coefficient for background)

QCD corrections enhance interference, similar to enhancement for signal

$$K_{signal} \sim K_{interf}$$

$m_h = 600$ GeV	$\sqrt{s} = 8$ TeV			$\sqrt{s} = 13$ TeV		
	LO	NLO	NNLO	LO	NLO	NNLO
σ_H	0.379	0.83(2)	1.07(5)	1.55	3.29(8)	4.2(2)
σ_{Hi}	0.427	0.93(3)	1.20(7)	1.66	3.5(1)	4.5(2)
$\sigma_H/\sigma_H^{\rm LO}$	—	2.19(5)	2.8(1)	—	2.13(5)	2.7(1)
$\sigma_{Hi}/\sigma_{Hi}^{\rm LO}$	—	2.19(7)	2.8(2)	—	2.12(6)	2.7(1)

Scope of the group

❑ **Providing theoretical guidelines, in common between CMS and ATLAS to**

- characterize properly heavy Higgs in the SM
  -> legacy results for SM limits up to 1 TeV

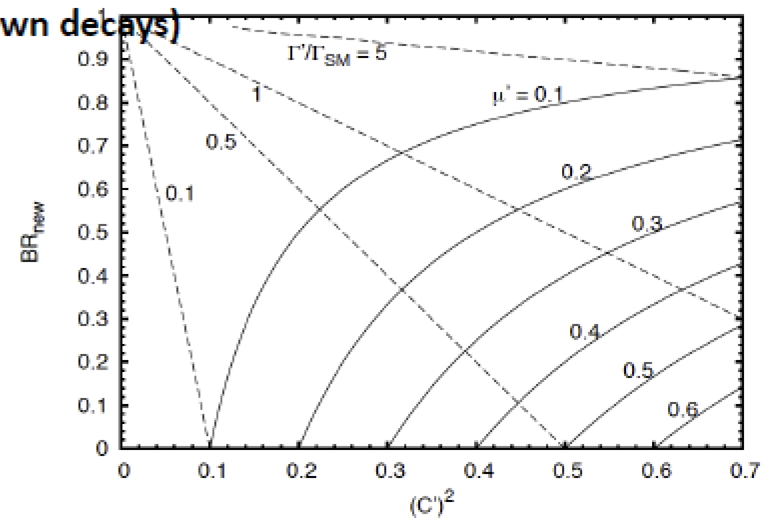
- define general benchmarks to reinterpret SM searches/ signatures in BSM scenarios. Starting from most basic ones:
  - SM Higgs mixed with EW-singlet *(today)*
  - 2HDM *(next meeting)*
  - Higgs triplet models
  - two near degenerate states at 126GeV in model-independent way
  - ...

  interests from experiments, to be worked out

- first discussions about more general study of EWSB mechanisms *(VV scattering workshop to be organized soon)*

Higgs mixed with EW-singlet

- **Two resonances with couplings rescaled wrt to SM**
  - coupling of h126 (h) = C × SM
  - coupling of heavy Higgs (H) ~ C' × SM
  - unitarization: $C'^2 + C^2 = 1$, ie $C' = \cos\theta$, $C = \sin\theta$ **-> 1 free parameter: θ mixing angle**
  - considering **H->hh decay (+ new unknown decays)**
    -> 1 additional free parameter (BR_{new})



- heavy Higgs search in **2 parameters space for each m_H hypotesis**

$$\mu' = C'^2(1-\mathrm{BR}_{new})$$

$$\Gamma'_{tot} = \frac{C'^2}{(1-\mathrm{BR}_{new})}\Gamma_{\mathrm{SM}}.$$

-> width different than SM

- observation of **h126 put experimental limits on value of mixing angle** (on possible width and xsec range for heavy mass search) $\mu_h' = \sin^2\theta \times \mu_h^{SM}$

- *Today talk: same kinematics, same QCD corrections and uncertainties as SM heavy Higgs !!!*
  -> all SM recipe/computations can be used… what about EWK-corrections?

Conclusions and agenda

❑ Work on-going for proper characterization of **heavy Higgs in general BSM scenarios:**

- **EWK singlet**: are the EWK corrections the same as in the SM case? If not, can they be easily computed?

  (today first talk:
  EWK-singlet and EWK corrections)

- **2HDM**: QCD corrections/uncertainties are being rescaled with modified couplings. What about EWK corrections?

  (next meeting will be devoted to 2HDM)

❑ Study of **heavy Higgs in SM: first step** needed to extend the recipes to BSM scenarios

SM calculations may often be redone/re-casted easily to these basic/general BSM scenarios

(today second talk:
gg->VV S+B+I at NNLO with soft collinear approx.)

Some discussion items

- Higgs mass peak shift: study with realistic detector effects (experimental and theoretical systematics)
- Higgs interferometry: is absolute determination of Higgs width and couplings important?

- VV: approximation of higher-order corrections for interference
- Impact on recipe for combination of (N)NLO S, LO I and B and improved uncertainty estimation
- Inclusion of EW corrections (in event generators?)

- Light SM Higgs discovered, therefore: heavy Higgs implies BSM
- Best way to adapt and use existing MC tools in BSM studies
- How to estimate/optimize theory uncertainty for BSM