Off-shell Higgs interference effects and width measurements in the *ZZ* decay channel

Raoul Röntsch

Fermilab

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Introduction

- $\Gamma_H/m_H \sim 10^{-5}$ – expect **NWA** to work well for Higgs.
- In H→ZZ→4l, ~10% of rate is in the high mass tail.

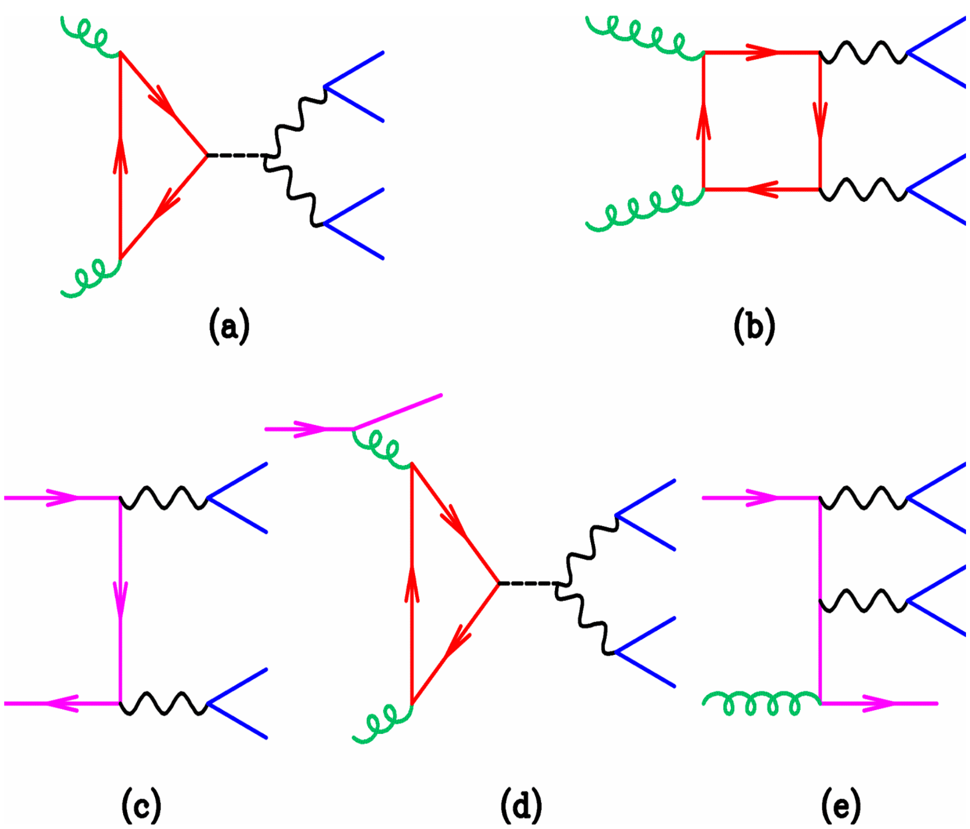
(Kauer, Passarino '12)

- **DRAMATIC** failure of NWA – **unitarizing feature** of Higgs.
- Can study **off-shell behavior of the Higgs.**
- Use this to bound the Higgs width (under certain assumptions):
  - On-peak: $\sigma \propto g_i^2 g_f^2/\Gamma_H$
  - Off-peak: $\sigma \propto g_i^2 g_f^2$

(Caola, Melnikov '13; Campbell, Ellis, Williams '13)

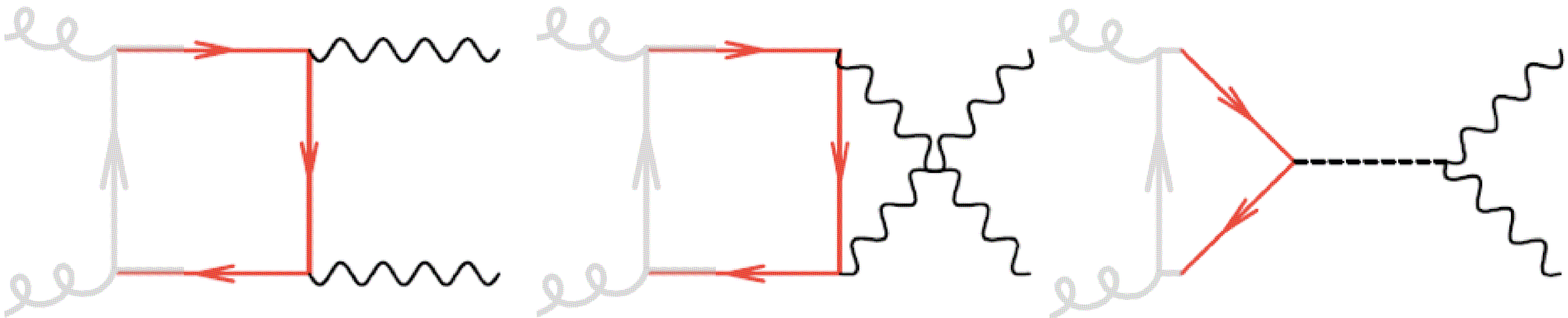
- I will focus on GLUON FUSION and H → ZZ DECAYS.

Theoretical ingredients



- |(a)|^2 – “signal”
- |(c)|^2 – “background (LO)”
- |(b)|^2 – “background (NNLO)”
- (a)*(b) – interference – **large** and **destructive** in high-mass tail (needed to unitarize high-energy behavior).
- (d)*(e) – interference at same order (gs^4) – expected to be less important

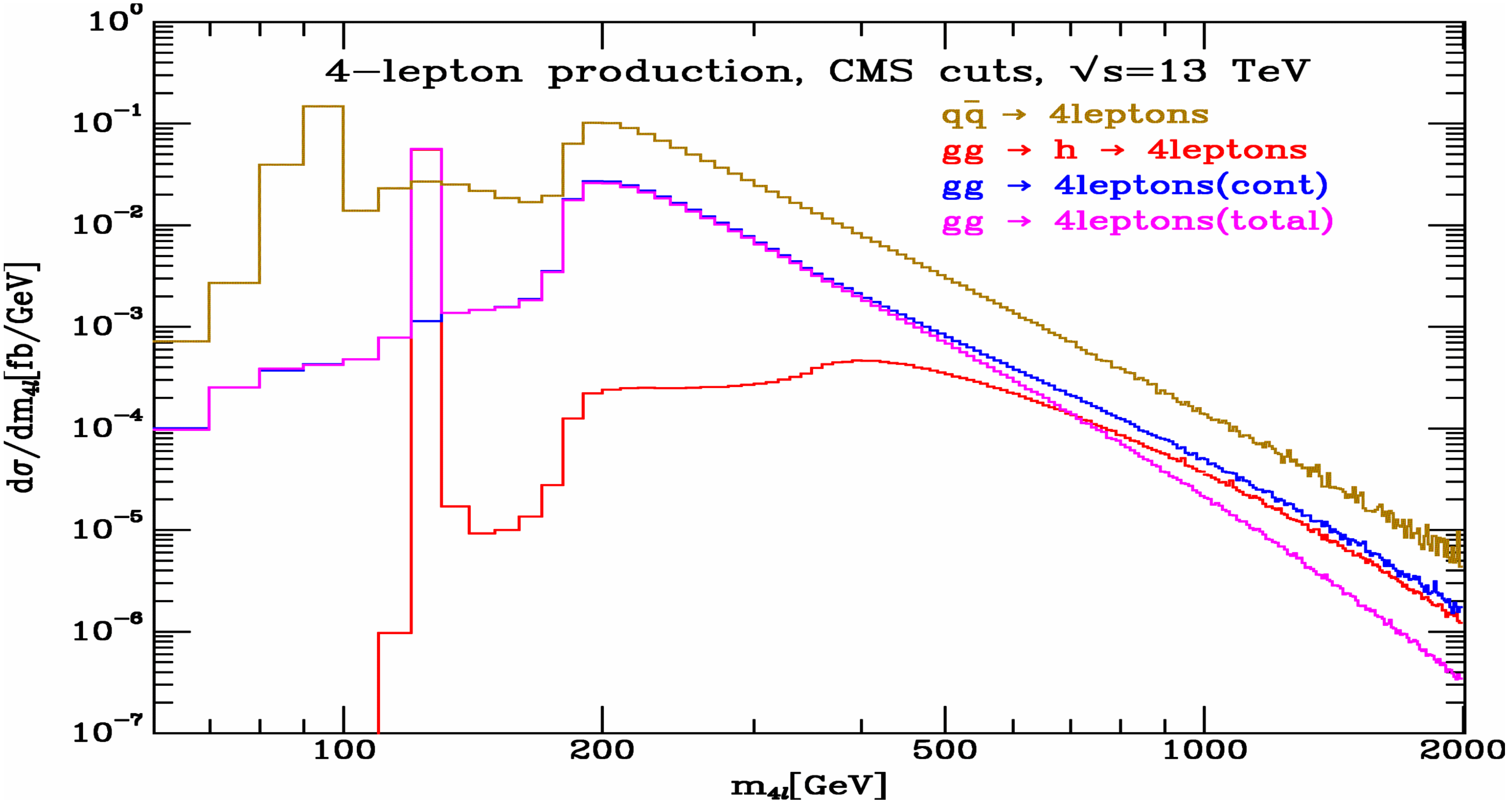
Understanding high energy behavior



$aE^2 + (b+c)m_t E$ $\quad$ $-aE^2 + (d-c)m_t E$ $\quad$ $-(b+d)m_t E$

- Higgs amplitude cancels high energy behavior and **preserves unitarity**.
- Higgs high mass behavior gives insight into its unitarizing properties.

Results



Interference has a significant effect!

Constraints on Higgs width

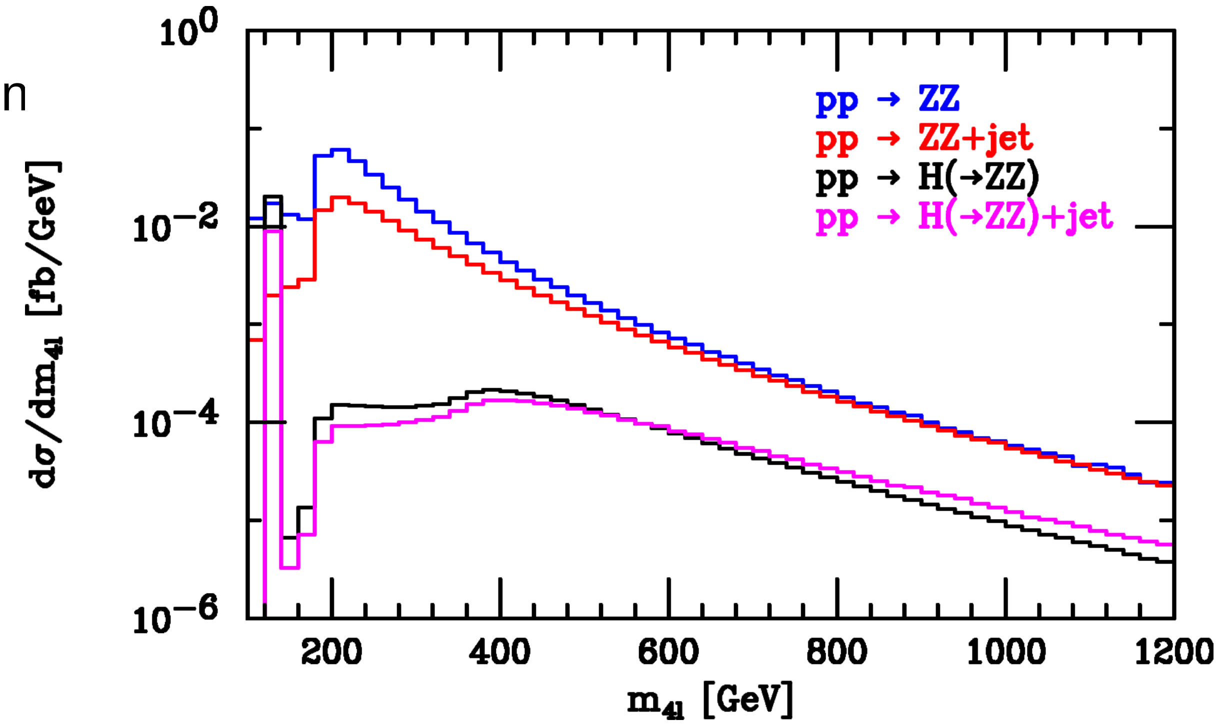
- Consider rescaling couplings and widths: $g_i \to \alpha g_i^{\rm SM};\ \Gamma_H \to \alpha^4 \Gamma_H^{\rm SM}$
    - On-shell cross-section *unchanged.*

$$\sigma_{\rm off} = \sigma_H \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - \sigma_I \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$

- Cut-and-count (Caola, Melnikov '13; Campbell, Ellis, Williams '13): $\Gamma_H \leq 25.2\ \Gamma_H^{\rm SM}$
- Matrix element method (Campbell, Ellis, Williams '13): $\Gamma_H \leq 15.7\ \Gamma_H^{\rm SM}$
- **ATLAS:** $\Gamma_H \leq (4.8 - 7.7)\ \Gamma_H^{\rm SM}$
- **CMS:** $\Gamma_H \leq 5.4\ \Gamma_H^{\rm SM}$

ZZ+jet (Campbell, Ellis, Furlan, RR, '14)

- 1-jet bin is well-populated (large radiation off *gg* initial state).
- Same effect should be present (and hence similar analysis should be possible) in this bin.
- Background smaller in 1-jet bin

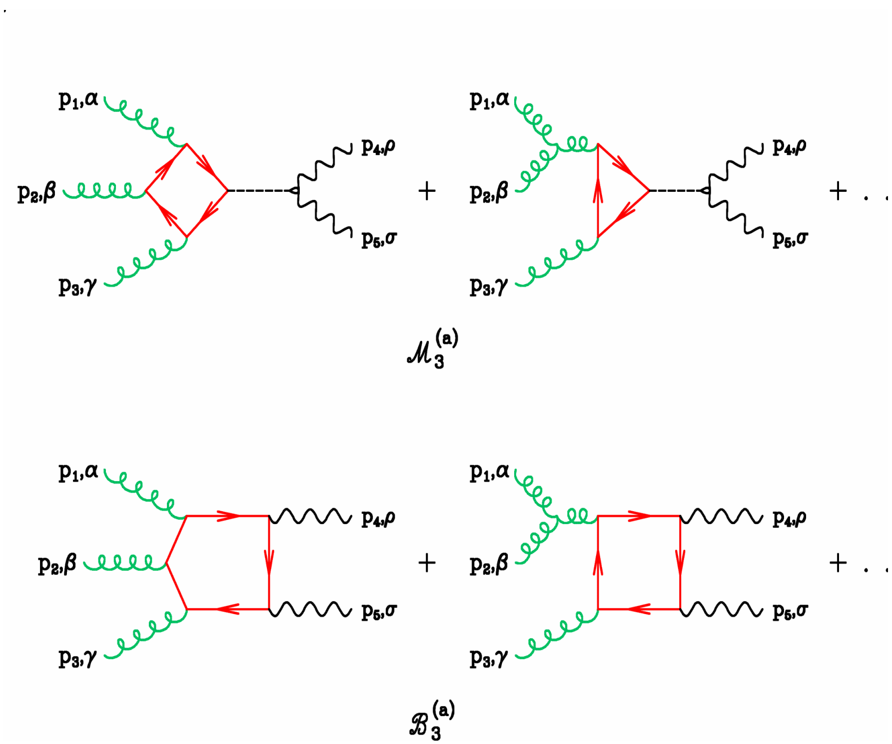


- Additionally: these amplitudes are needed for real radiation corrections to gg → H → ZZ and gg → ZZ.

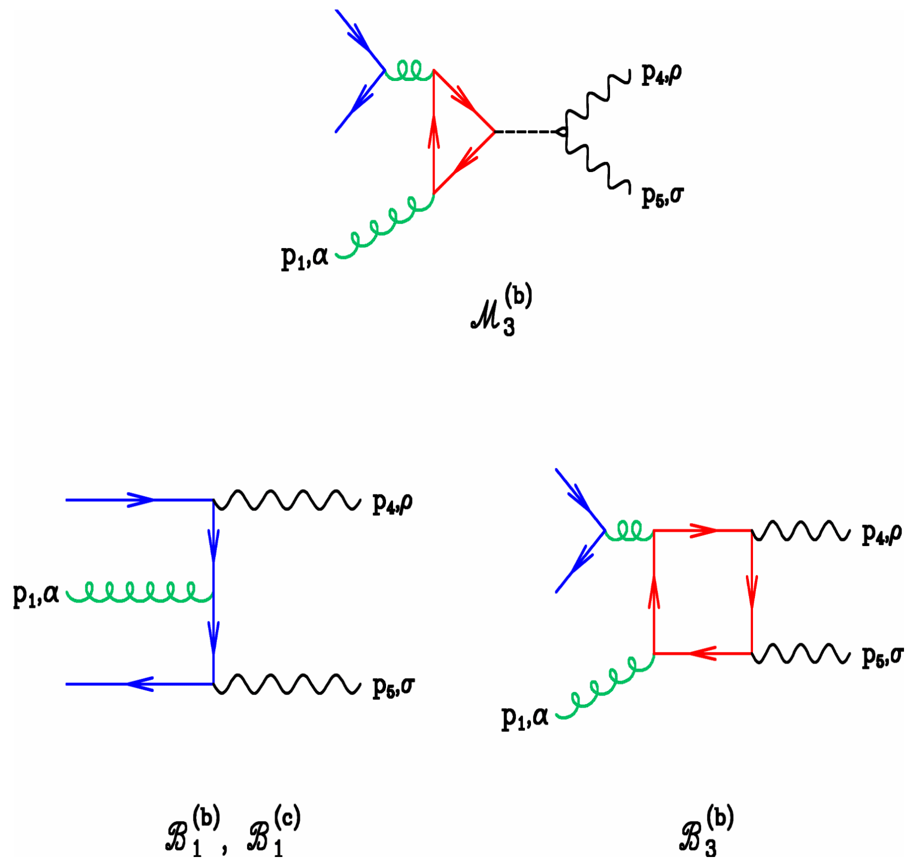
  [bottleneck: virtual corrections for gg → ZZ (two-loop)]

Theoretical ingredients

Gluon-initiated



Quark-initiated.



- Dominant contribution
- Cf. Campanario, Li, Rauch, Spira '13

- Box*Triangle not negligible in tail
- Other interferences small (Binoth *et. al.* '10)

Results in partonic channels

- Z decays included through BR only.
- Require jet with |η| < 3 and pT > pT,cut
- Dynamic scale μ = mZZ/2
- Results shown in tail mZZ > 300 GeV

	$p_{T,\text{cut}}$ [GeV]	σ_H^{gg} [fb]	$\sigma_H^{qg+q\bar{q}}$ [fb]	σ_I^{gg} [fb]	$\sigma_I^{qg+q\bar{q}}$ [fb]	σ_I^{tree} [fb]
$\sqrt{s} = 8$ TeV	30	0.0212	0.00679	-0.0299	-0.00929	0.00230
	50	0.0124	0.00522	-0.0173	-0.00706	0.00182
	100	0.00467	0.00279	-0.00632	-0.00369	0.00097
	200	0.00104	0.00086	-0.00133	-0.00111	0.00026
$\sqrt{s} = 13$ TeV	30	0.0887	0.0216	-0.1263	-0.0298	0.00652
	50	0.0547	0.0172	-0.0770	-0.0235	0.00528
	100	0.0229	0.0101	-0.0313	-0.0136	0.00298
	200	0.00612	0.00377	-0.00798	-0.00497	0.00092

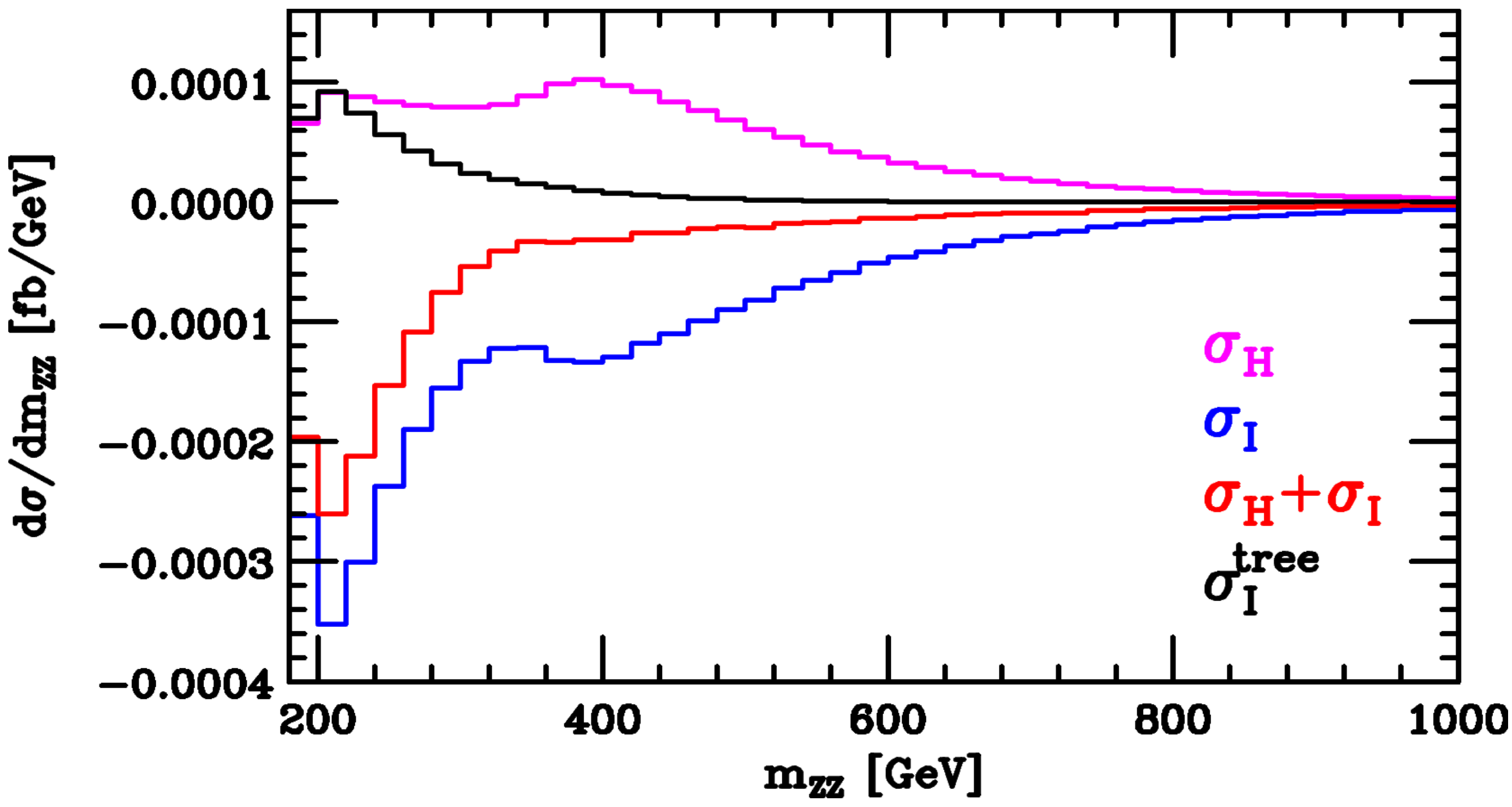
- Quark-initiated contributions amount to **25-50%** at 8 TeV, smaller at 13 TeV.
- “Loop” interference contributions are large and negative (req'd by unitarity).
- “Tree” interference are small.

Results

	$p_{T,\mathrm{cut}}$ [GeV]	$\sigma_{H,\mathrm{peak}}$ [fb]	$\sigma_{H,\mathrm{tail}}$ [fb]	$\sigma_{I,\mathrm{tail}}$ [fb]	$\sigma^{tree}_{I,\mathrm{tail}}$ [fb]
$\sqrt{s} = 8$ TeV	30	0.351	0.0280	-0.0392	0.0023
	50	0.206	0.0176	-0.0244	0.0018
	100	0.0714	0.0075	-0.0100	0.0010
	200	0.0128	0.0019	-0.0024	0.00026
$\sqrt{s} = 13$ TeV	30	0.909	0.110	-0.156	0.0065
	50	0.557	0.0718	-0.100	0.0053
	100	0.212	0.0329	-0.0448	0.0030
	200	0.045	0.0099	-0.0130	0.0009

- Higgs off-peak ~ order of magnitude smaller than on-peak cross-section.
- **A few events in high-mass tail already produced in run I.**
- Increase by factor 4-5 for run II.
- Tree interference – upper bound on this effect.

Results



- Interference has dramatic effect on shape as well as normalization.

Higgs width analysis in ZZ+jet

- Recall $\sigma_{\rm off} = \sigma_H \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - \sigma_I \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$
- For gg → ZZ → 4l : $\sigma_{\rm off} = 0.025 \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 0.036 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$
- For gg → ZZ: $\sigma_{\rm off} = 0.0323 \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 0.0468 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$
- For ZZ + jet: $\sigma_{\rm off} = 0.0280 \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 0.0392 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$

Theoretical control

- Background process pp → ZZ well controlled – known to NNLO (Cascioli *et. al.* '14)
- "Signal" and "interference" processes gg → H → ZZ and gg → ZZ in these analyses – LO only.
  - gg → H known to NLO (i.e. two loops)
  - gg → ZZ (with internal masses) at LO only.
  - Amplitudes for real radiation known (ZZ+jet)
  - Bottleneck: gg → ZZ (with internal masses) at two loops

Theoretical control

- Interference terms negligible for widths far from SM – but ATLAS & CMS **already close to SM width**.
- Rescaling assumes that higher order corrections same in interference as in Higgs squared.
- Confirmed in the case of heavy Higgs

  (Bonvini et. al. '13)

  – but for lighter Higgs?
- CMS adopts 10% scale uncertainty as systematic: realistic?