Interference effects and the Higgs Width

Raoul Röntsch

Fermilab

BSM Higgs Workshop @ LPC
Fermilab, November 3 2014

Introduction

- Higgs width unambiguously predicted in SM: $\Gamma_H^{\mathrm{SM}} = 4.07 \times 10^{-3}\ \mathrm{GeV}$
- Larger width suggestive of decays to new states.
- Involved in extraction of Higgs couplings.
- **BUT:** detector resolution @ LHC ~ 1 GeV – direct measurement (e.g. scanning cross-section about mH) not possible.
  - (One motivation for future linear collider).
- Use indirect means to bound width @ LHC.
  - Global fits
  - "Inferometry"
    - Mass peak shifts in $H \to \gamma\gamma$
    - interference in $gg \to ZZ$
  - ...

Higgs Width from Coupling Fits

- Theoretically well-motivated assumption:

  $|C_{Z,W}| < 1.5$

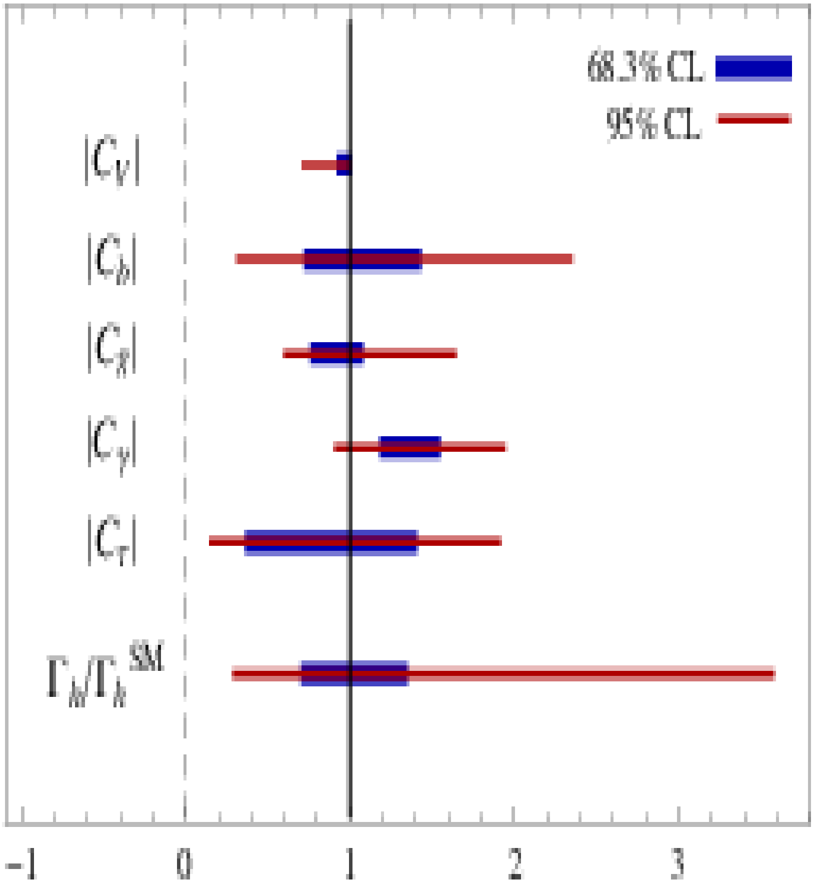
- Higgs coupling fits to *WW, ZZ, γγ, bb, gg, ττ*

  → Upper bound on Higgs width

  $$\Gamma_H/\Gamma_H^{\mathrm{SM}} \leq 0.52^{+0.82}_{-0.10}$$

  (Dobrescu, Lykken, hep-ph/1210.3342)

  (see also Djouadi, Moreau, hep-ph/1303.6591, CMS PAS-HIG-13-005)



Higgs Width from Coupling Fits

- Lower limit on coupling extracted from rate required for observation.

$$\Gamma_H/\Gamma_H^{\rm SM} \geq 1.05^{+1.26}_{-0.34}$$

- Combining these limits: $0.71 \leq \Gamma_H/\Gamma_H^{\rm SM} \leq 1.34$

- Model dependence/theoretical assumptions...

Higgs Mass Peak Shift in $H \to \gamma\gamma$

- Real part of interference between gg → γγ and gg → H → γγ is **odd** about Higgs peak.

  (Dircus, Willenbrock, PRD37,1801)

  - Interference effects in overall cross section is **small** (mostly come from imaginary part of two-loop gg → γγ)

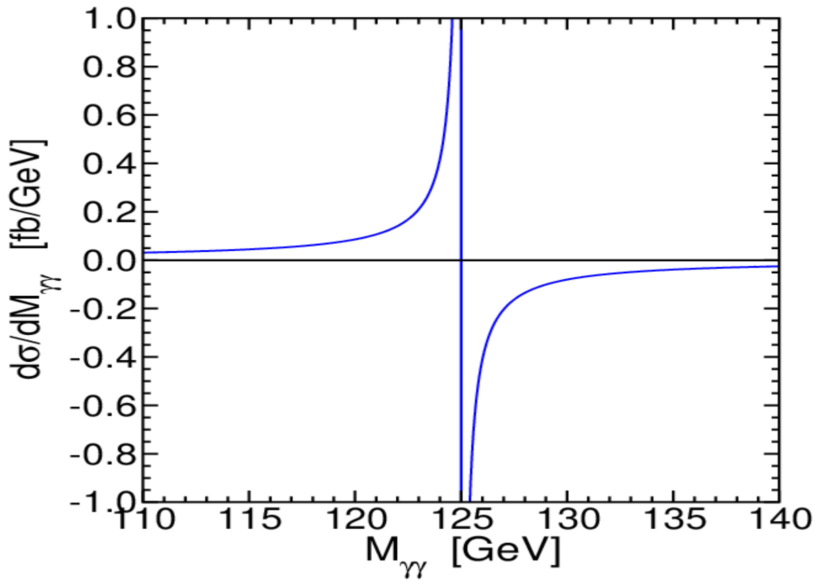
    (Dixon, Siu, hep-ph/0302233)

  - Shift mass peak to lower values by ~ 100 MeV – important for precise mass determinations!

    (Martin, hep-ph/1208.1533, hep-ph/1303.3342,

    De Florian *et al.*, hep-ph/1303.1397,

    Dixon, Li, hep-ph/1305.3854)



- Strongly dependent on higher-order corrections
  - Shift **decreased** by including qg tree-level interference
  - Shift **decreased** by including NLO gg interference
  - Shift **increased** by including NLO qg interference
- Also strongly dependent on detector (+ other experimental) effects

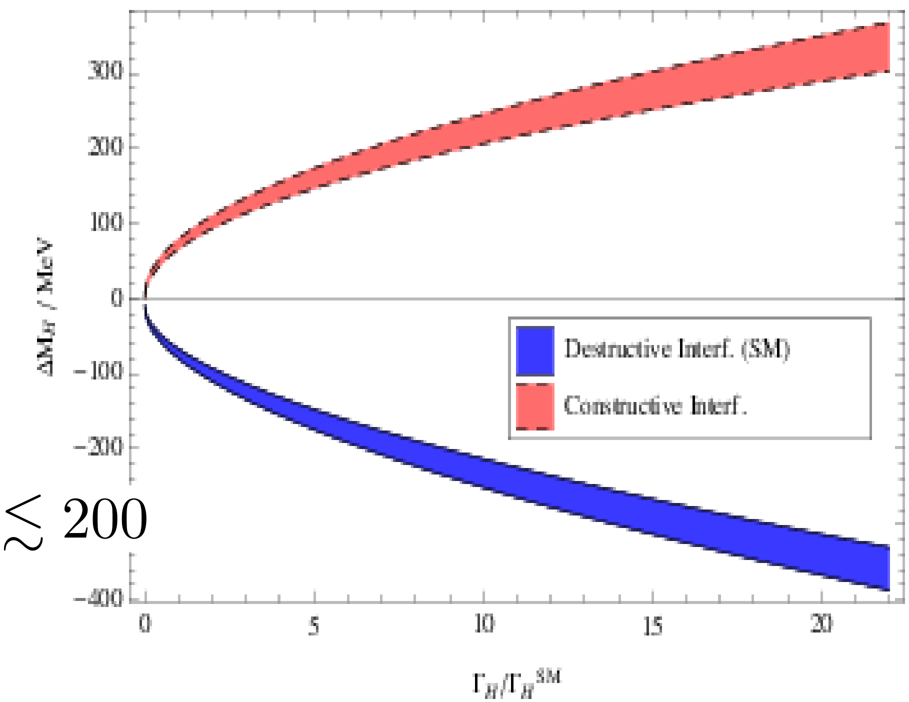
Bounding Higgs Width with Mass Peak Shift

$$\frac{d\sigma^{\text{int}}}{dM_{\gamma\gamma}} = \frac{(M_{\gamma\gamma}^2 - m_H^2)R + m_H \Gamma_H I}{(M_{\gamma\gamma}^2 - m_H^2) + m_H^2 \Gamma_H^2}$$

~1%, can be ignored

$\sim c_g c_\gamma$

Overall rate $\sim c_g^2 c_\gamma^2 / \Gamma_H$



- Mass shift *R* and overall rate can be related to Higgs width.
- Current data indicates $\Gamma_H / \Gamma_H^{\text{SM}} \lesssim 200$
- With 3 ab^-1, $\Gamma_H / \Gamma_H^{\text{SM}} \lesssim 15$

(Dixon, Li, hep-ph/1305.3854)

Interference in *gg* → *H* → *ZZ*

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

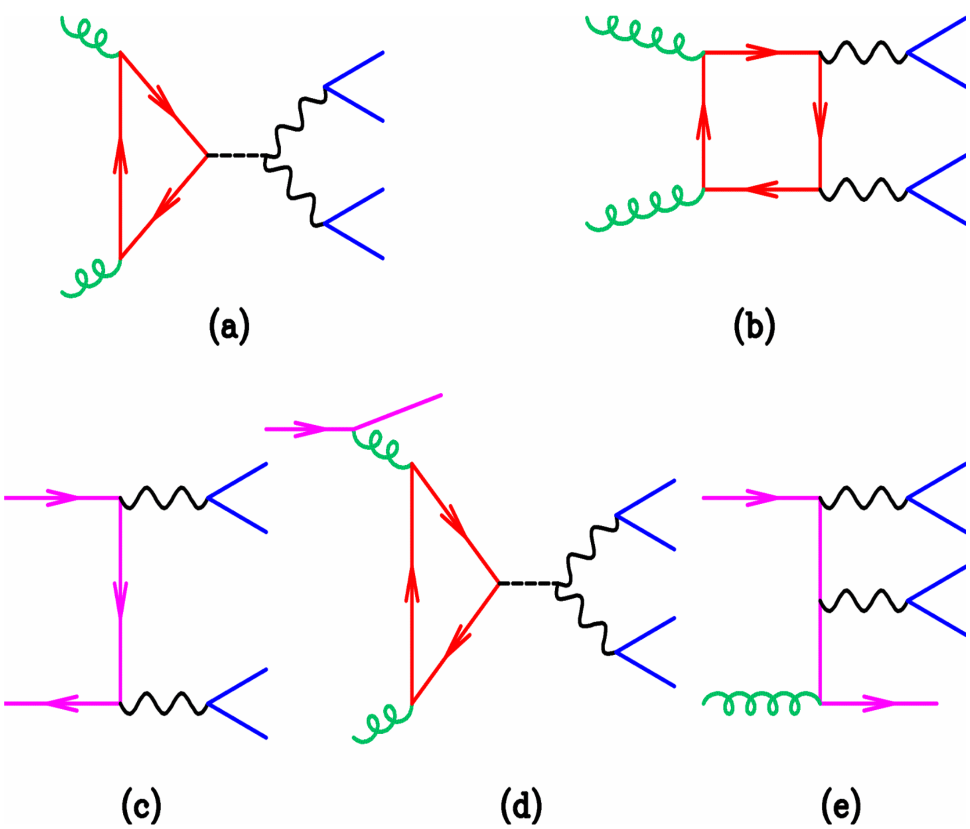
(Kauer, Passarino hep-ph/1206.4803)

- **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 hep-ph/1307.4935; Campbell, Ellis, Williams hep-ph/1311.3589, hep-ph/1312.1628)

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

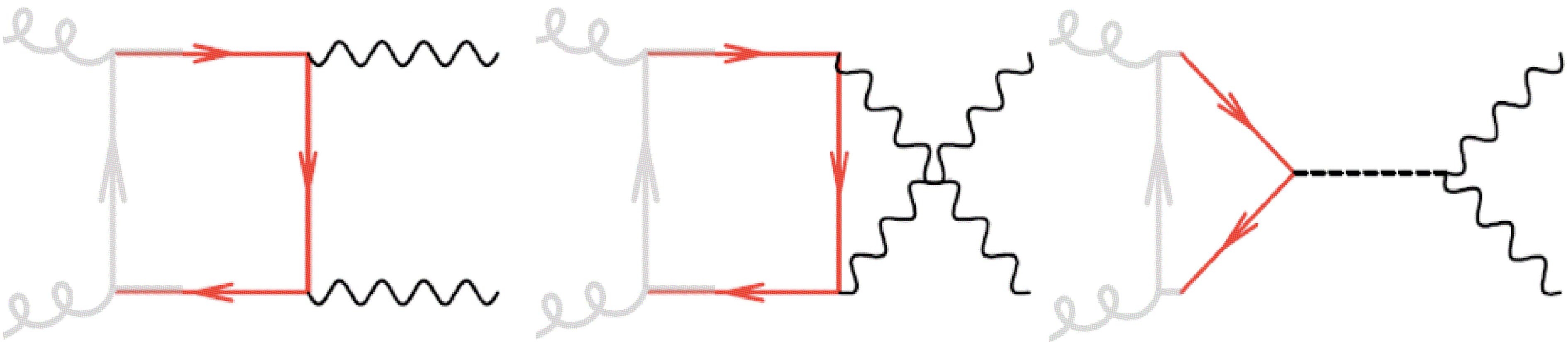
Theoretical ingredients



- |(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

Look at *ttb* → *ZZ*

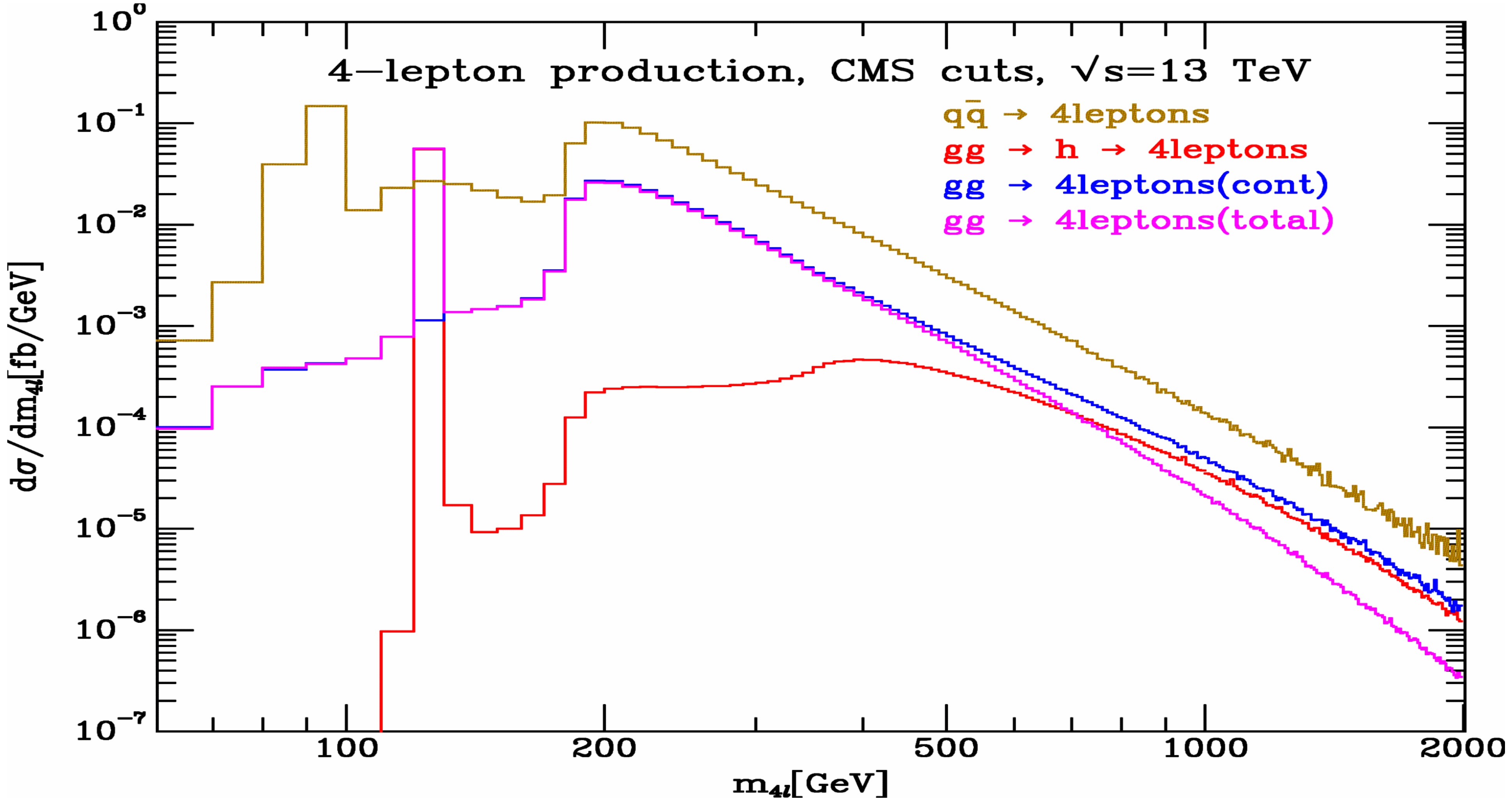


$aE^2 + (b+c)m_t E$ $-aE^2 + (d-c)m_t E$ $-(b+d)m_t E$

Courtesy J. Campbell

- 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!

Constraining the Higgs width

- Consider rescaling couplings and widths: $g_i \to \alpha g_i; \Gamma_H \to \alpha^4 \Gamma_H$
  - On-shell cross section remains 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 $\Gamma_H \leq 25.2\ \Gamma_H^{\rm SM}$

  (Caola, Melnikov hep-ph/1307.4935;

  Campbell, Ellis, Williams hep-ph/1311.3589, hep-ph/1312.1628)

- Matrix element methods $\Gamma_H \leq 15.7\ \Gamma_H^{\rm SM}$

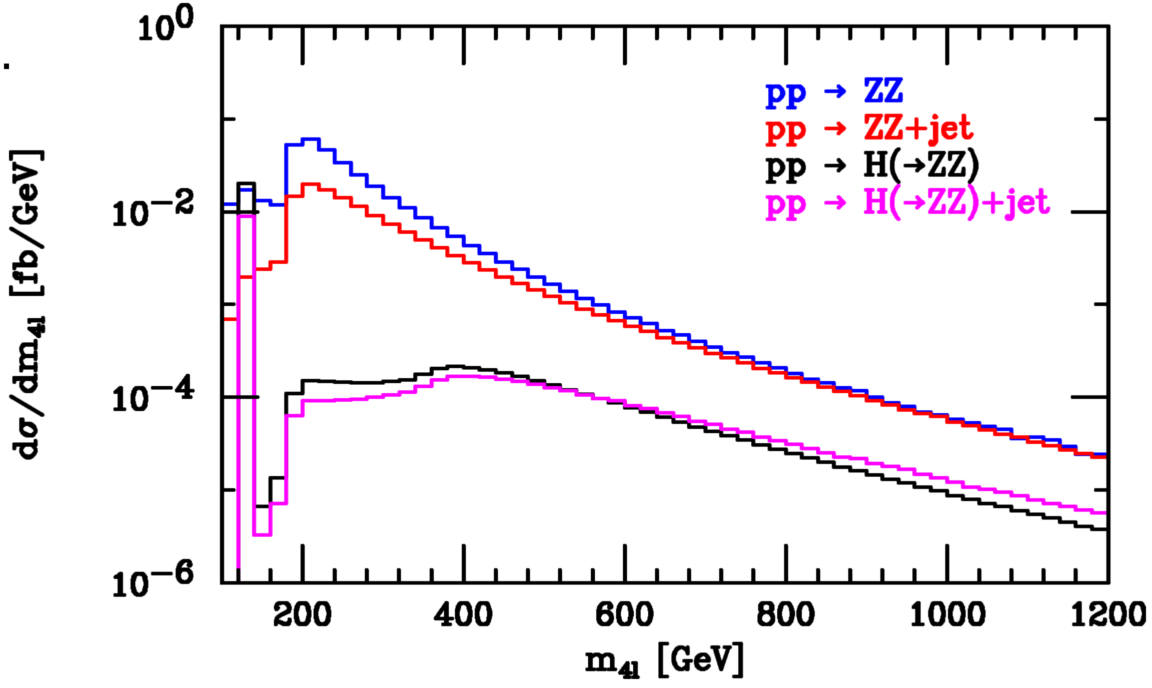
  (Campbell, Ellis, Williams hep-ph/1311.3589)

- **ATLAS** $\Gamma_H \leq (4.8 - 7.7)\ \Gamma_H^{\rm SM}$ ATLAS-CONF-2014-042

- **CMS** $\Gamma_H \leq 5.4\ \Gamma_H^{\rm SM}$ hep-ex/1405.3455

ZZ+jet (Campbell, Ellis, Furlan, RR, hep-ph/1409.1897)

- 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.

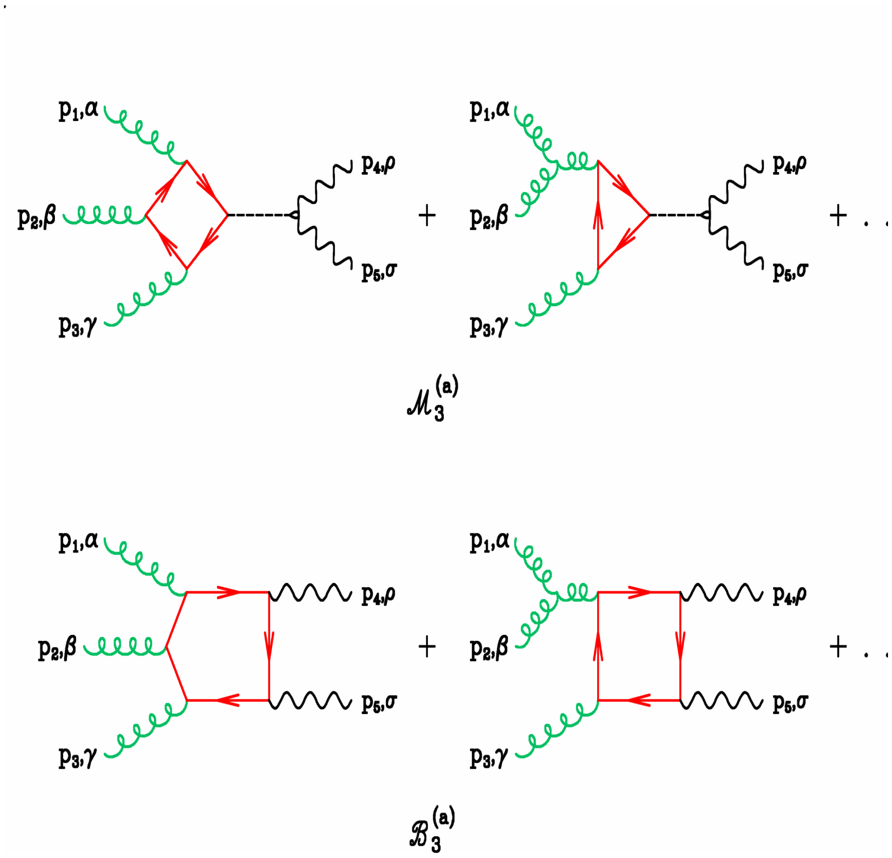


- Additionally: these amplitudes are needed for real radiation corrections to gg → H → ZZ and gg → ZZ.

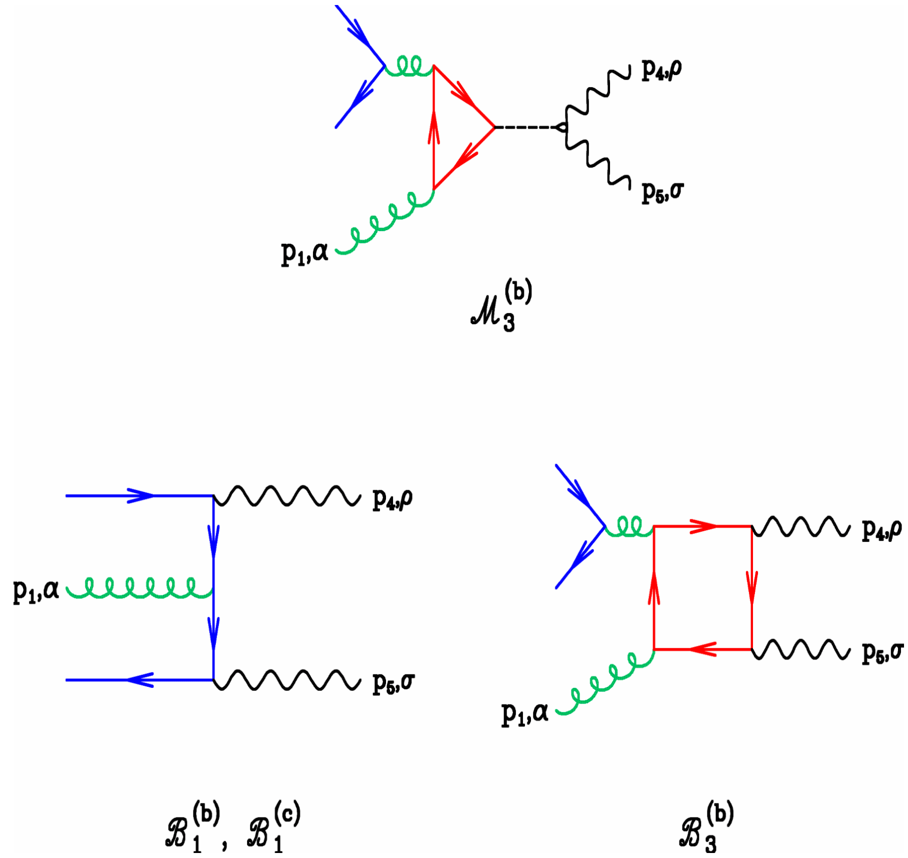
[bottleneck: virtual corrections for gg → ZZ (two-loop)]

Theoretical ingredients

Gluon-initiated



Quark-initiated.



- Dominant contribution
- Cf. Campanario, *et al,* hep-ph/1211.5429

- Box*Triangle not negligible in tail
- Other interferences small (Binoth *et. al.*, hep-ph/0911.3181)

Results in partonic channels

- *Z* kept on-shell: decays included through BR only.

  (only valid for mZZ > 2 mZ)
- Look at tail mZZ > 300 GeV
- Require jet with $|\eta| < 3$ and pT > pT,cut
- Dynamic scale μ = mZZ/2

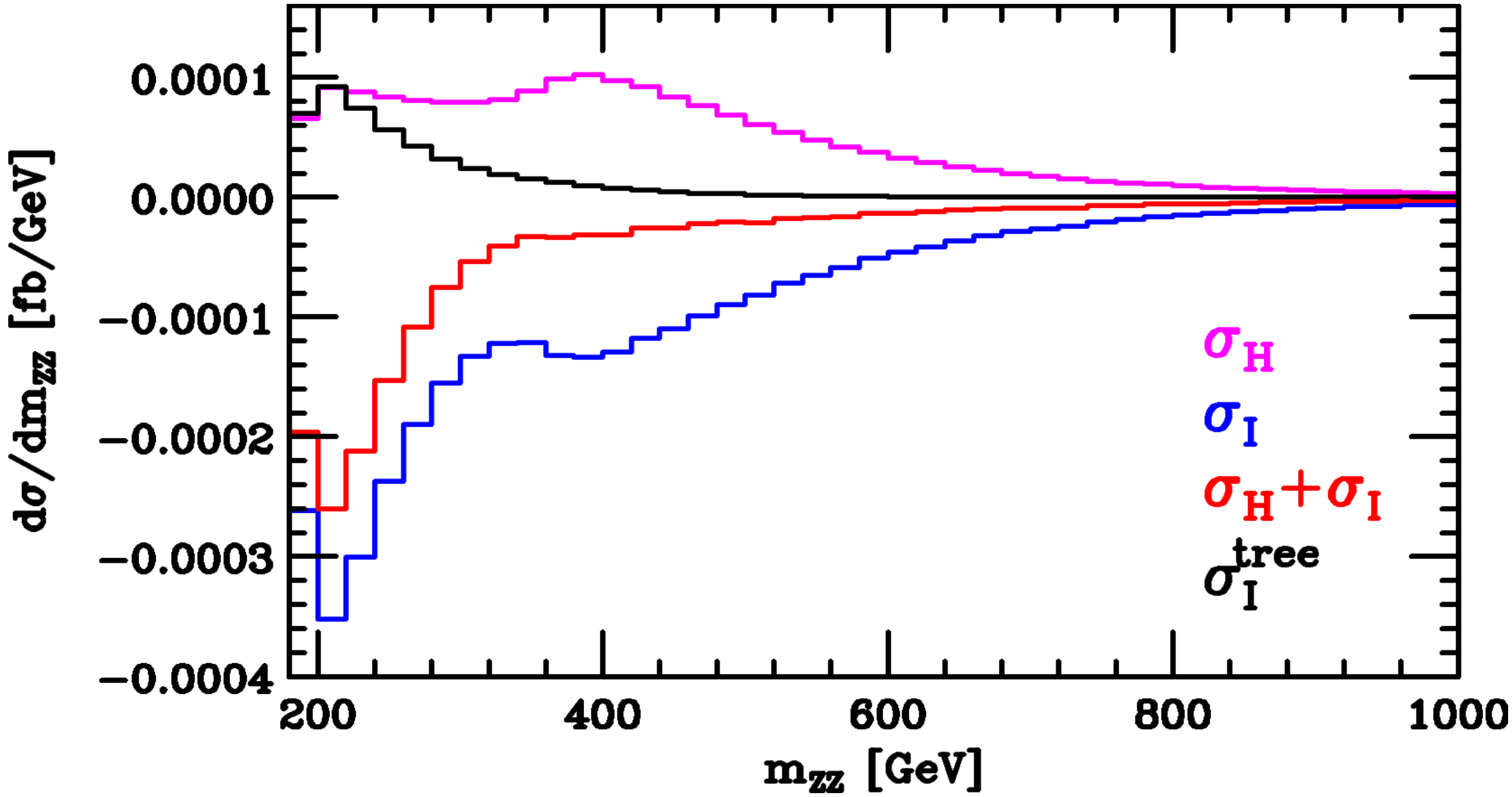
- Quark-initiated contributions amount to **25-50%** at 8 TeV, smaller at 13 TeV.
- “Loop” interference contributions are large and negative (req'd by unitarity).
- “Tree” interference are small.

Results

	$p_{T,\text{cut}}$ [GeV]	$\sigma_{H,\text{peak}}$ [fb]	$\sigma_{H,\text{tail}}$ [fb]	$\sigma_{I,\text{tail}}$ [fb]	$\sigma_{I,\text{tail}}^{tree}$ [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.
- 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: $$\sigma_{\rm off} = 0.0280 \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 0.0392 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$
- Expect comparable width constraints in 1-jet bin

Theoretical control

- Background process pp → ZZ well controlled – known to NNLO (Cascioli *et. al.* hep-ph/1405.2219)
- "Signal" and "interference" processes gg → H → ZZ and gg → ZZ in these analyses – **LO only.**
  - *gg* → *H* has large scale uncertainty & *k*-factor
  - Full dependence on mt required.
  - 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

- *gg* → *ZZ* contributes to interference terms.
- Recall $$\sigma_{\rm off} = \sigma_H \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - \sigma_I \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$
- 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 using SCET

  (Bonvini *et. al.* hep-ph/1304.3053)

  – but for lighter Higgs?

Model independence

- Critical assumption: Higgs couplings on-shell same as those off-shell.
- New particles in loop may violate this (see Englert, Spannowsky, hep-ph/1409.8074, Englert, Soreq, Spannowsky hep-ph/1410.5440)
- For BSM scenarios satisfying

$$R_{m_{ZZ}} = \kappa_{ggH}(m_H^2)/\kappa_{ggH}(m_{ZZ)} \simeq 1$$

  the interpretation as a width constraint is **valid**.
- Examples: Dimension-6 extension of Higgs sector with Higgs portal, minimal extension of Higgs sector.
- Not valid for, e.g. MSSM
  - But here, off-shell effects excellent probe for light stops

Conclusions

- Indirect measurements of Higgs width possible at the LHC.
  - Global fits, mass peak shift in $\gamma\gamma$ decay, off-peak effects in ZZ decay
- Off-peak effects in ZZ decay:
  - Possible because of unitarizing feature of Higgs
  - Inclusion of interference effects is essential
  - Analysis also possible in 1-jet bin (also VBF?)
  - Work ongoing to extend analysis to NLO
- All indirect measurements have theoretical assumptions – careful interpretation of width constraints.
  - Understand validity of interpretation within various BSM scenarios.

THANK YOU