Off-shell Effects and the Higgs Width

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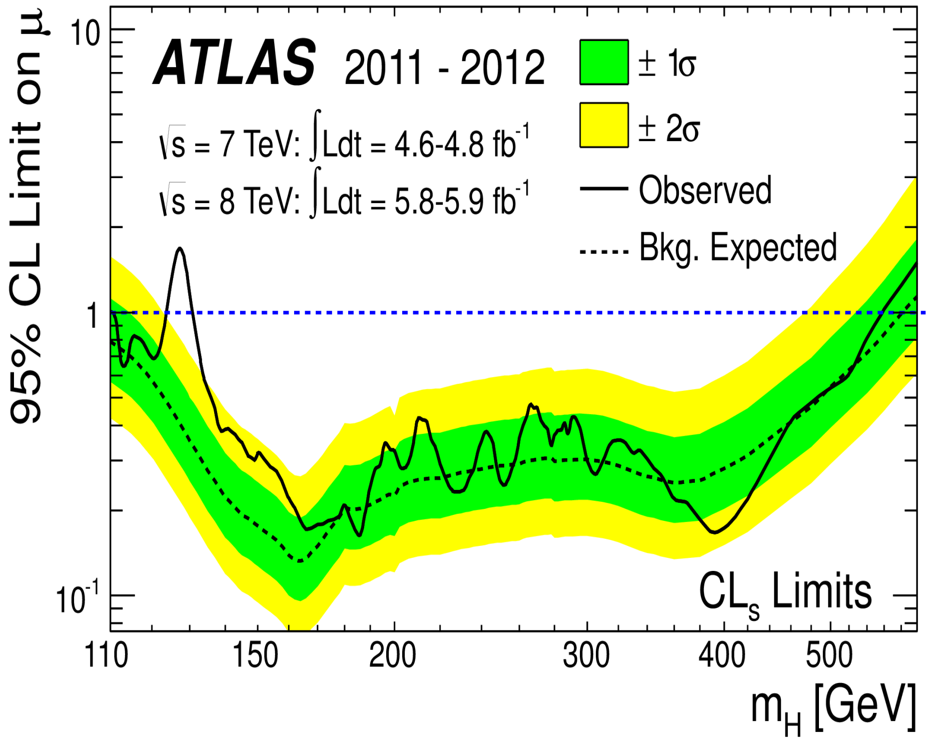
Outline

- Introduction / Motivation
- Interference in GF $H \to VV$:
  - Inclusive production $H \to ZZ$
  - One-jet bin $H \to ZZ$
  - Inclusive production $H \to WW$
  - Theoretical control
  - Model independence
- Interference in VBF $H \to ZZ$.
- Other indirect constraints on Higgs width
  - Interference in $H \to \gamma\gamma$
  - Global fit
- Conclusions

Introduction

We found the Higgs!



Now we should measure its properties:

- Mass
- Width
- CP properties
- Production cross sections
- Couplings to other particles
- ...

Nature of the Higgs boson – SM or not?

Nature of the EW symmetry breaking mechanism

High energy behavior of the Higgs

Other than these properties of the particle, it is worth examining the kinematic behavior of the Higgs – in particular its **high energy behavior.**

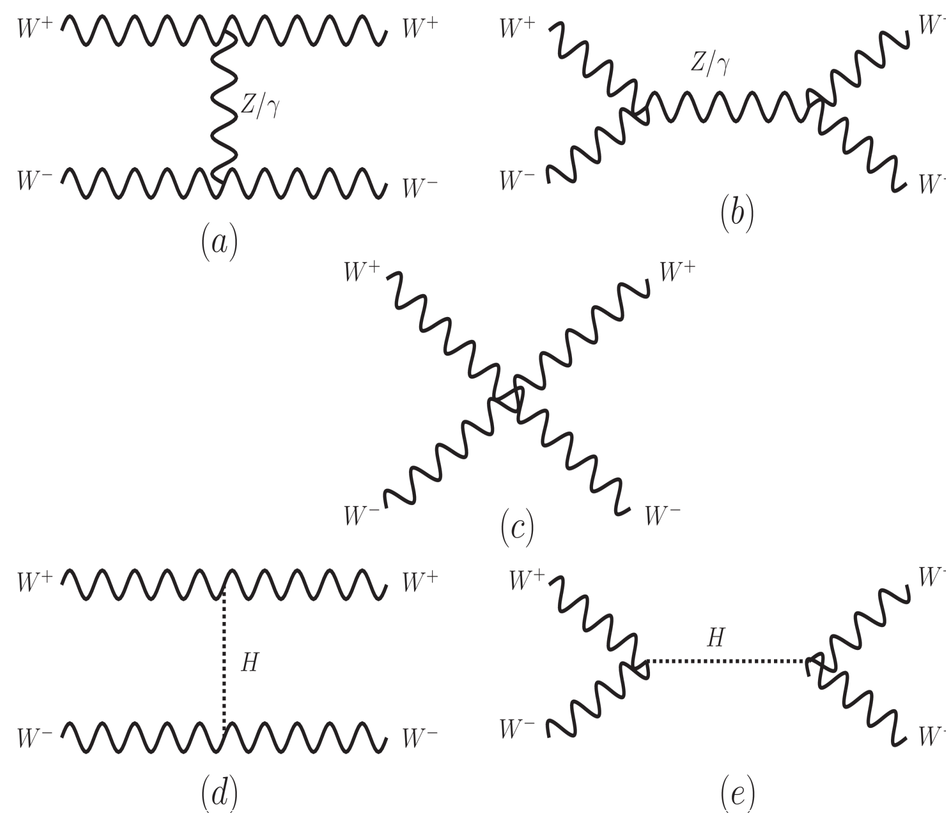
- In gluon fusion (GF), new particles in loop resolved at high energies.
- High energy behavior probes unitarizing nature of the Higgs.

Unitarization of scattering with massive gauge bosons

- Consider W+W- → W+W- scattering
- Higgs mechanism breaks EW symmetry & gives mass to W & Z bosons.
- Longitudinal modes give rise to amplitudes ~E in (a), (b), (c) -

  Violate unitarity at high energy
- Exactly canceled by Higgs s-channel and t-channel exchange [(d) and (e)] – **unitarity preserved.**

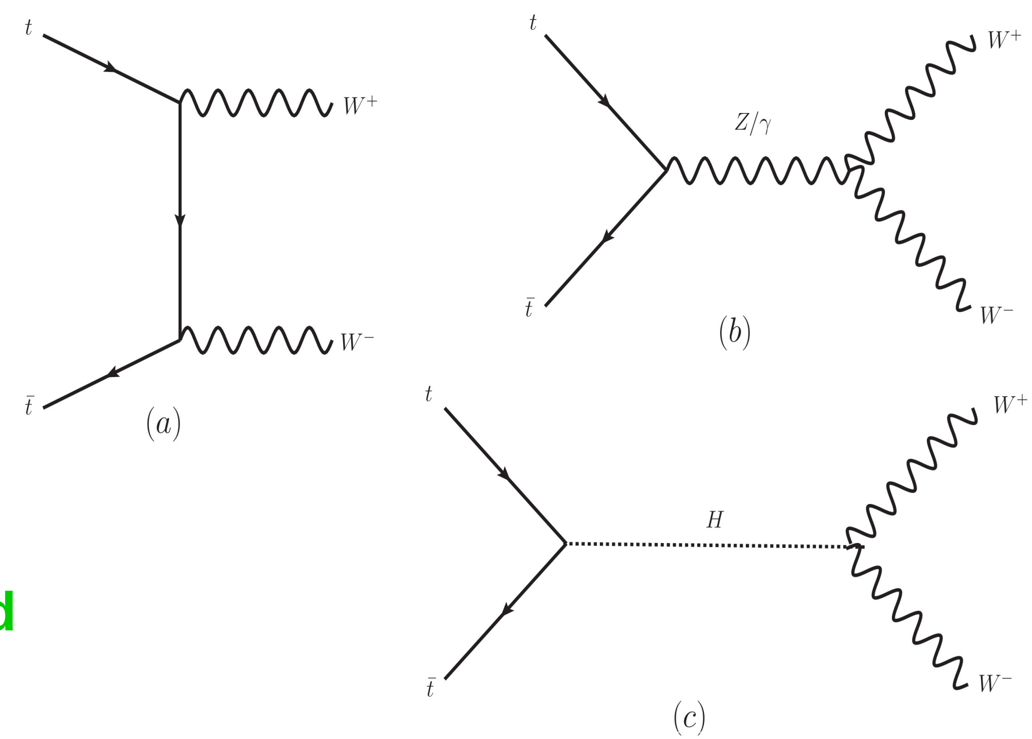
Higgs mechanism creates both the problem and the solution.



Unitarization of interactions with massive fermions

Consider t tbar → W+W-

- Higgs mechanism gives mass to fermions – helicity no longer well-defined
- Amplitudes for “wrong” helicity fermions interacting with longitudinal gauge bosons [(a), (b)] ~ mE – **violates unitarity**
- Exactly canceled by Higgs exchange (c) – **unitarity preserved**
- **Relationship between Yukawa interactions and fermion mass crucial!**



Unitarizing properties are a fundamental feature of the EWSB mechanism

(see C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*)

Unitarization and Interference

- Unitarity preservation requires cancellations at the **amplitude level** between longitudinal gauge bosons and Higgs boson.
- At the **amplitude squared** (cross section) **level** - large, destructive interference effects between "signal" and "background" processes.
- Need to understand interference effects in high-energy region – "**Higgs interferometry**"

Interference in *gg* → *H* → *ZZ*

- In H→ZZ→4l, ~10% of rate is in the high mass tail.

  (Kauer, Passarino hep-ph/1206.4803)

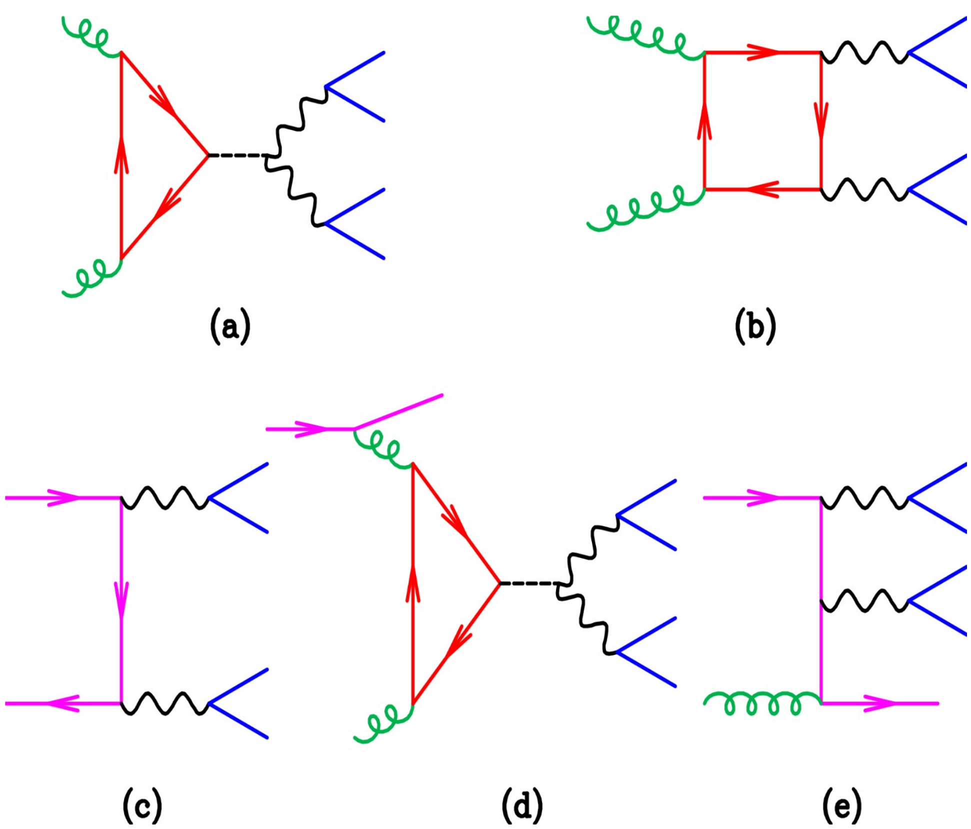
- Despite $\Gamma_H/m_H \sim 10^{-5}$ – **DRAMATIC** failure of NWA

- Off-shell behavior in H → ZZ:
  - Unitarization effects
  - Off-shell couplings
  - Higgs width (under certain assumptions)

(Caola, Melnikov hep-ph/1307.4935

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

Theoretical ingredients

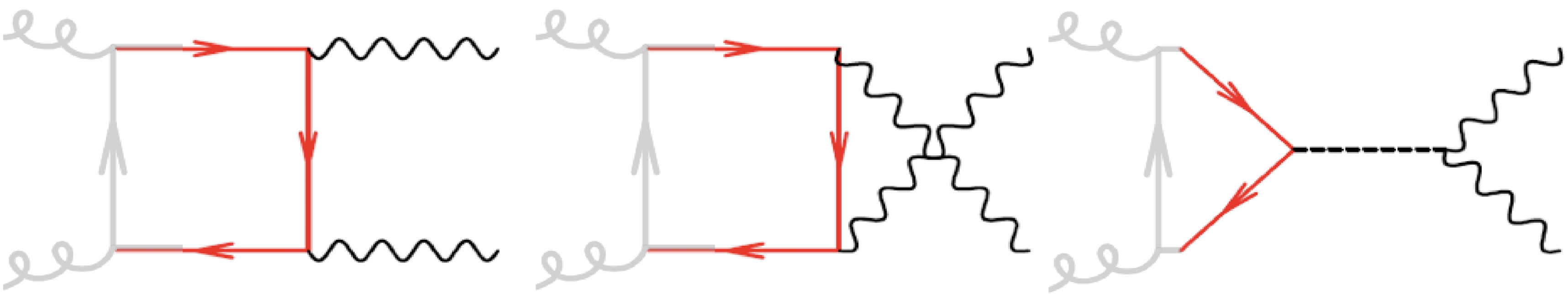


- |(a)|^2 – "signal"
- |(b)|^2 – "background (NNLO)"
- (a)*(b) – interference – **large** and **destructive** in high-mass tail
- |(c)|^2 – "background (LO)"
- (d)*(e) – interference at same order (gs^4) – expected to be less important
  [no unitarity violation in (e)]

Understanding high energy behavior

Cut open top loop – have ttbar → ZZ

(similar to ttbar → WW)



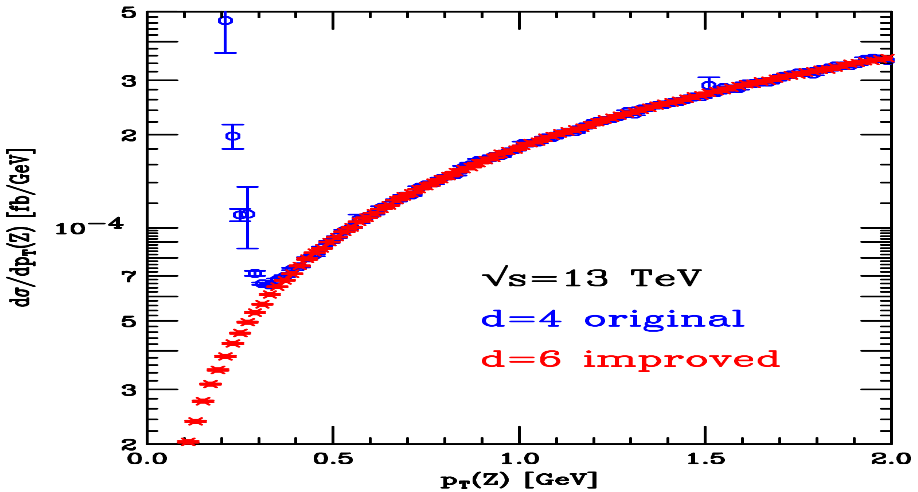
$aE^2 + (b+c)m_tE$ $\quad$ $-aE^2 + (d-c)m_tE$ $\quad$ $-(b+d)m_tE$

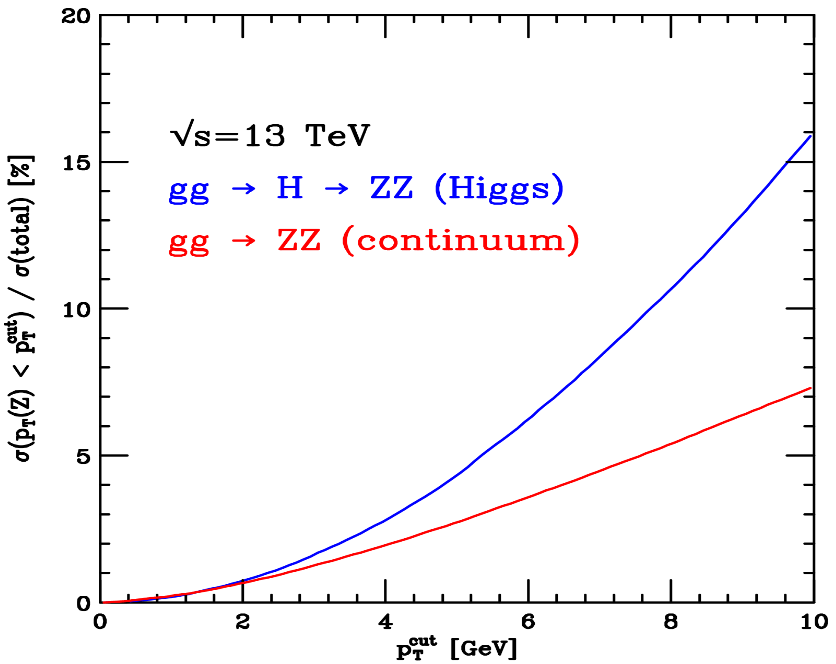
Courtesy J. Campbell

- Gauge invariance cancels E^2 terms and one E term
- Remaining E terms canceled by Higgs-mediated amplitude
- “Signal” and “background” amplitudes have important **high-energy behavior**
- Large destructive interference between them

Treatment of low $p_{T,Z}$

- Spurious $1/p_{T,Z}$ poles appear in “background” amplitudes
- Fixed by cuts on $p_{T,Z}$, but this does not correspond to experimental setup.
- Removal of all $1/p_{T,Z}^4$ and $1/p_{T,Z}^3$ poles allows stable result with $p_{T,Z}$ =0.1 GeV
  – minimal impact on cross sections



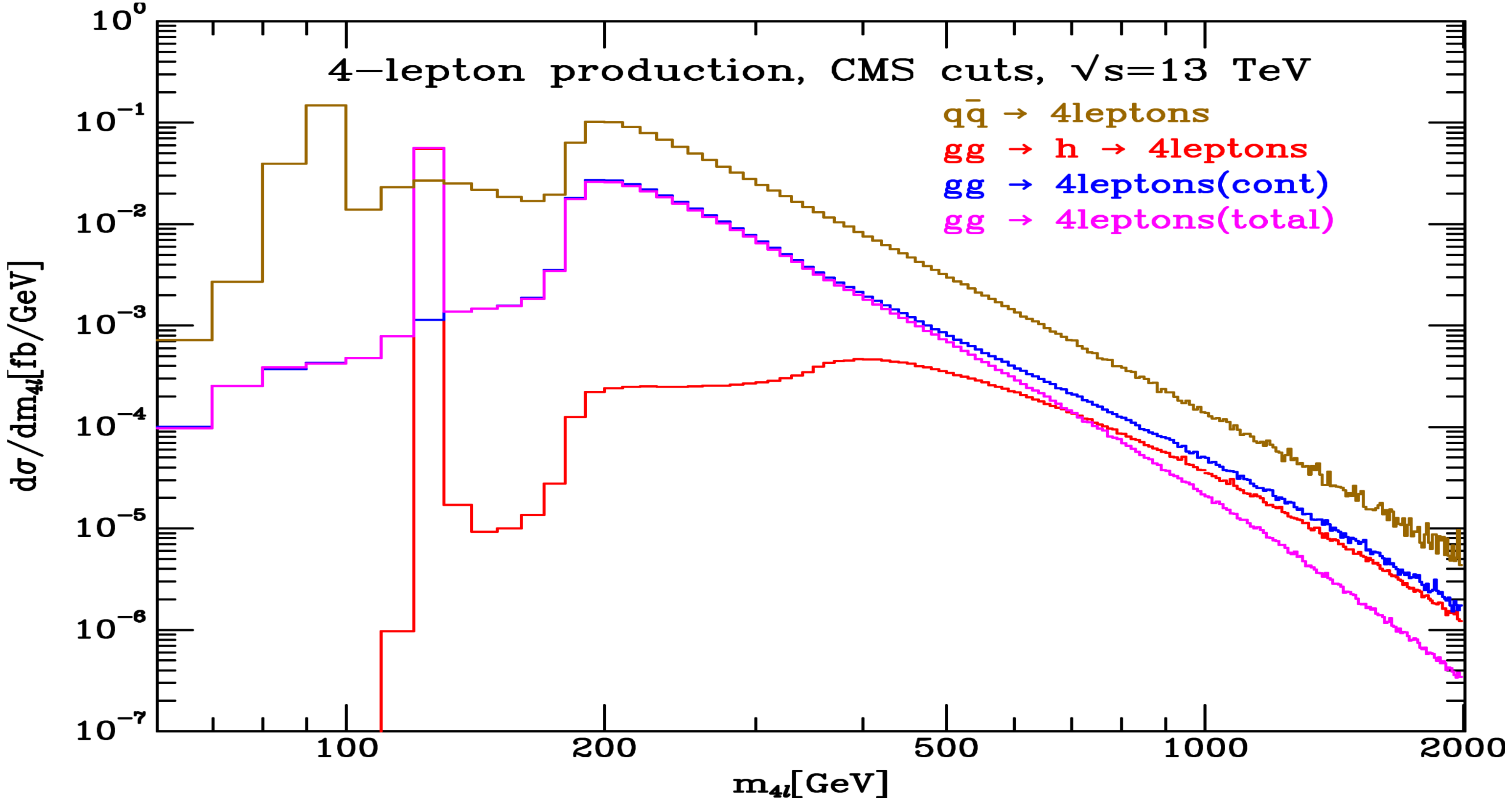


Implementation and Results

- Process gg → H → ZZ → 4l implemented in MCFM
- High mass tail →need full mass dependence in loop (heavy top approx. not valid)
- Implementation at **LO** (i.e. one-loop) only
- Results using cuts on leptons following CMS.

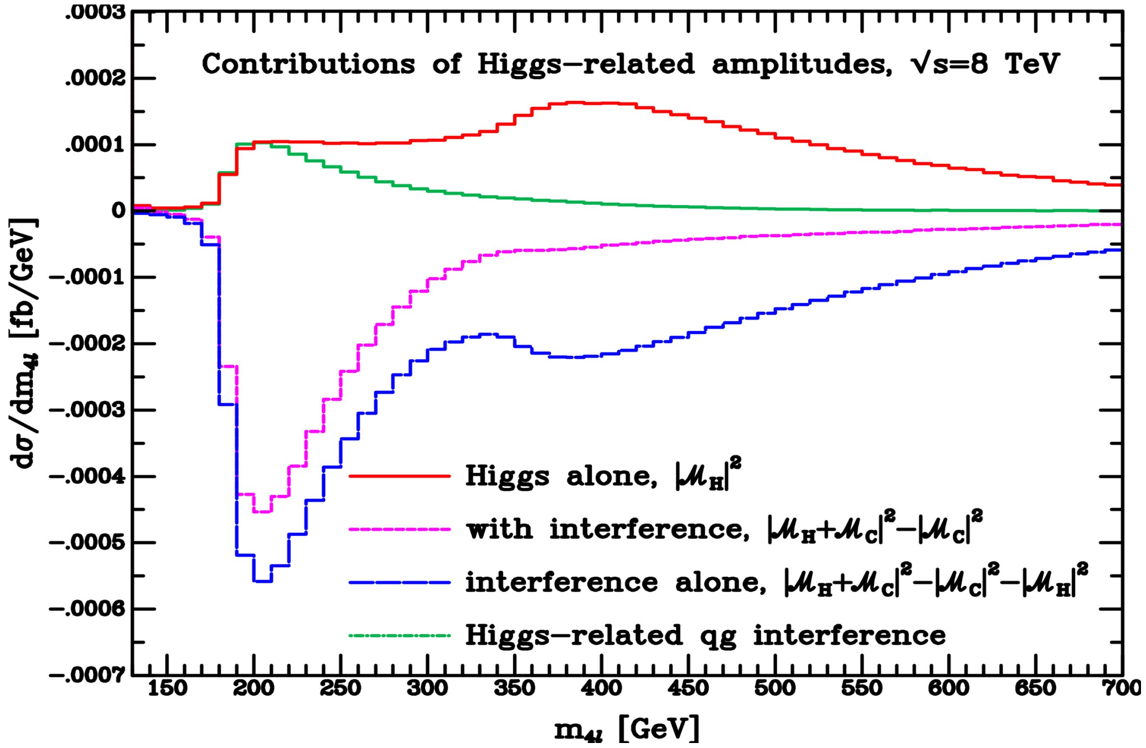
- See hep-ph/1311.3589

Results



Interference reduces rate by almost order of magnitude in high energy tail!

Partonic channels



- Interference also has significant impact on shape of distribution
- Interference from *qg* channel smaller, always positive (no unitarity requirements at this order)

Scale and pdf effects

PDF set	Scale	σ^H_{peak}	$\sigma^H_{off}(m_{4\ell} > 130\text{ GeV})$	$\sigma^I_{off}(m_{4\ell} > 130\text{ GeV})$	$\left(\sigma^H_{off} + \sigma^I_{off}\right) / \sigma^H_{peak}$
MSTW	$m_H/2$	0.256	0.061	-0.118	-0.223
	$m_{4\ell}/2$	0.255	0.035	-0.073	-0.149
CTEQ	$m_H/2$	0.242	0.052	-0.103	-0.252
	$m_{4\ell}/2$	0.243	0.029	-0.065	-0.148

PDF set	Scale	σ^H_{peak}	$\sigma^H_{off}(m_{4\ell} > 300\text{ GeV})$	$\sigma^I_{off}(m_{4\ell} > 300\text{ GeV})$	$\left(\sigma^H_{off} + \sigma^I_{off}\right) / \sigma^H_{peak}$
MSTW	$m_H/2$	0.256	0.049	-0.071	-0.086
	$m_{4\ell}/2$	0.255	0.026	-0.036	-0.039
CTEQ	$m_H/2$	0.242	0.041	-0.059	-0.074
	$m_{4\ell}/2$	0.243	0.021	-0.031	-0.041

$\sqrt{s}$=8 TeV

- High mass tail (> 300 GeV) ~4-9% of peak cross section
- Pdf choice ~5% on-peak, ~15-20% in tail
- Scale mH/2 not motivated in tail
- Substantial scale uncertainty in tail
- Relative importance of tail increases by factor ~ 1.5 at $\sqrt{s}$=13 TeV

Constraining the Higgs width

- 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 coupling
- **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 (e.g. interferometry) to measure/constrain width at LHC

Constraining the Higgs width

- On-peak cross section: $\sigma \propto g_i^2 g_f^2 / \Gamma_H$
- Off-peak cross section: $\sigma \propto g_i^2 g_f^2$

- Consider rescaling couplings and widths such that on-peak rate unchanged:

$$g_i \to \alpha g_i; \Gamma_H \to \alpha^4 \Gamma_H$$

- Off-peak cross section is then

$$\sigma_{\text{off}} = \alpha^4 \sigma_H - \alpha^2 \sigma_I \Rightarrow \boxed{\sigma_{\text{off}} = \sigma_H \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - \sigma_I \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}}$$

- E.g. at √s=8 TeV $\sigma_{\text{off}} = 0.025 \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 0.036 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}$

Constraining the Higgs width

- Cut-and-count $\Gamma_H \leq 25.2\ \Gamma_H^{\mathrm{SM}}$

  (Caola, Melnikov hep-ph/1307.4935;

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

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

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

- **ATLAS** $\Gamma_H \leq (4.8 - 7.7)\ \Gamma_H^{\mathrm{SM}}$

  ATLAS-CONF-2014-042

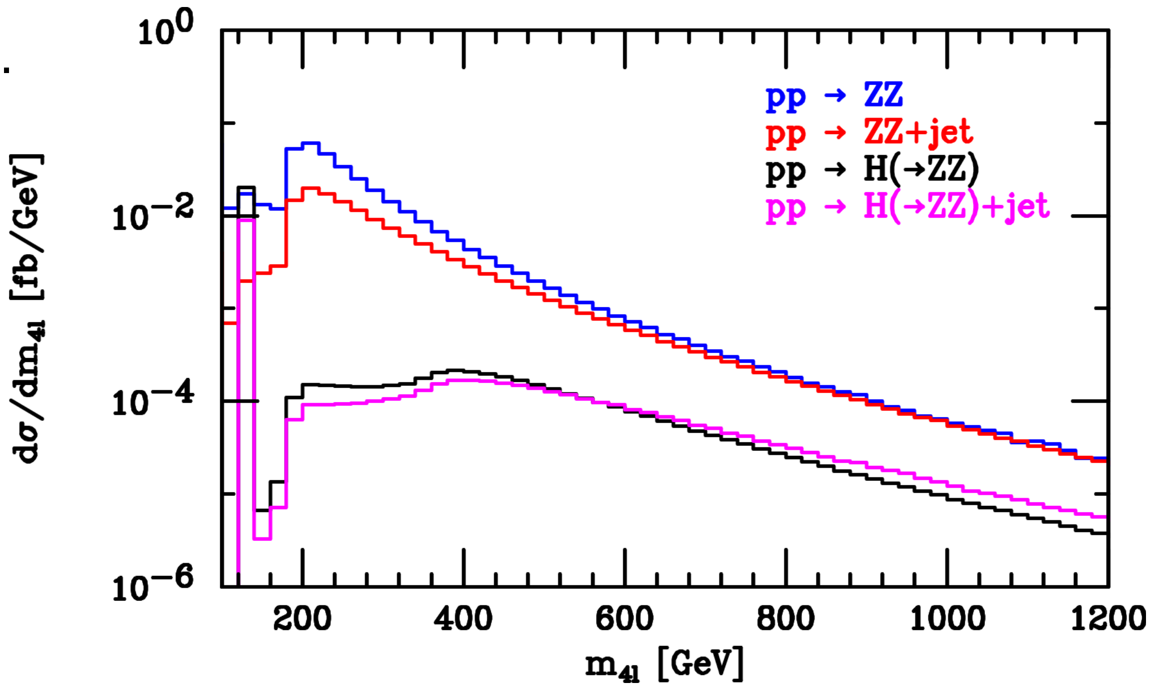
- **CMS** $\Gamma_H \leq 5.4\ \Gamma_H^{\mathrm{SM}}$

  hep-ex/1405.3455

- Theoretical control, model independence....

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.

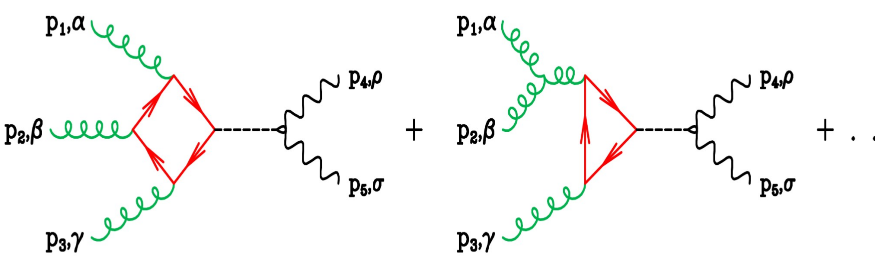


- Additionally: these amplitudes are needed for real radiation corrections to gg → H → ZZ and gg → ZZ.

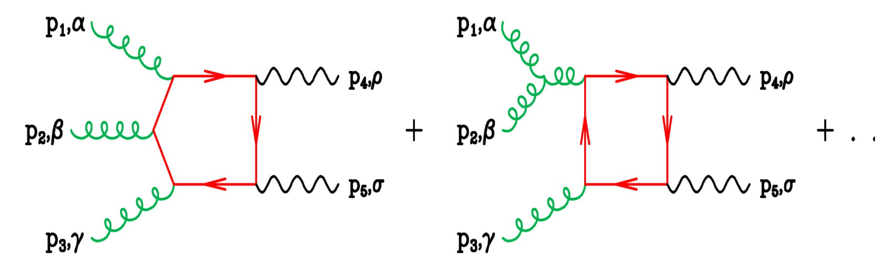
  [bottleneck: virtual corrections for gg → ZZ (two-loop)]

Theoretical ingredients

Gluon-initiated



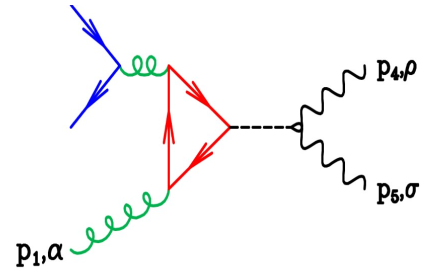
$\mathcal{M}_3^{(a)}$



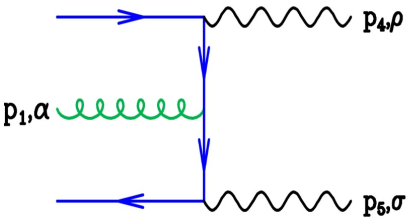
$\mathcal{B}_3^{(a)}$

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

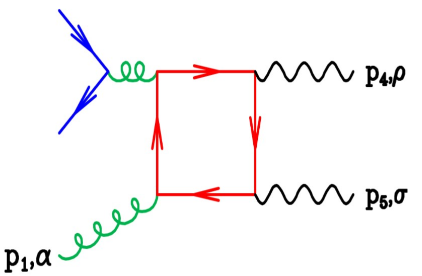
Quark-initiated.



$\mathcal{M}_3^{(b)}$



$\mathcal{B}_1^{(b)}$, $\mathcal{B}_1^{(c)}$



$\mathcal{B}_3^{(b)}$

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

Results in partonic channels

- Implemented in MCFM (not yet public)
- *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

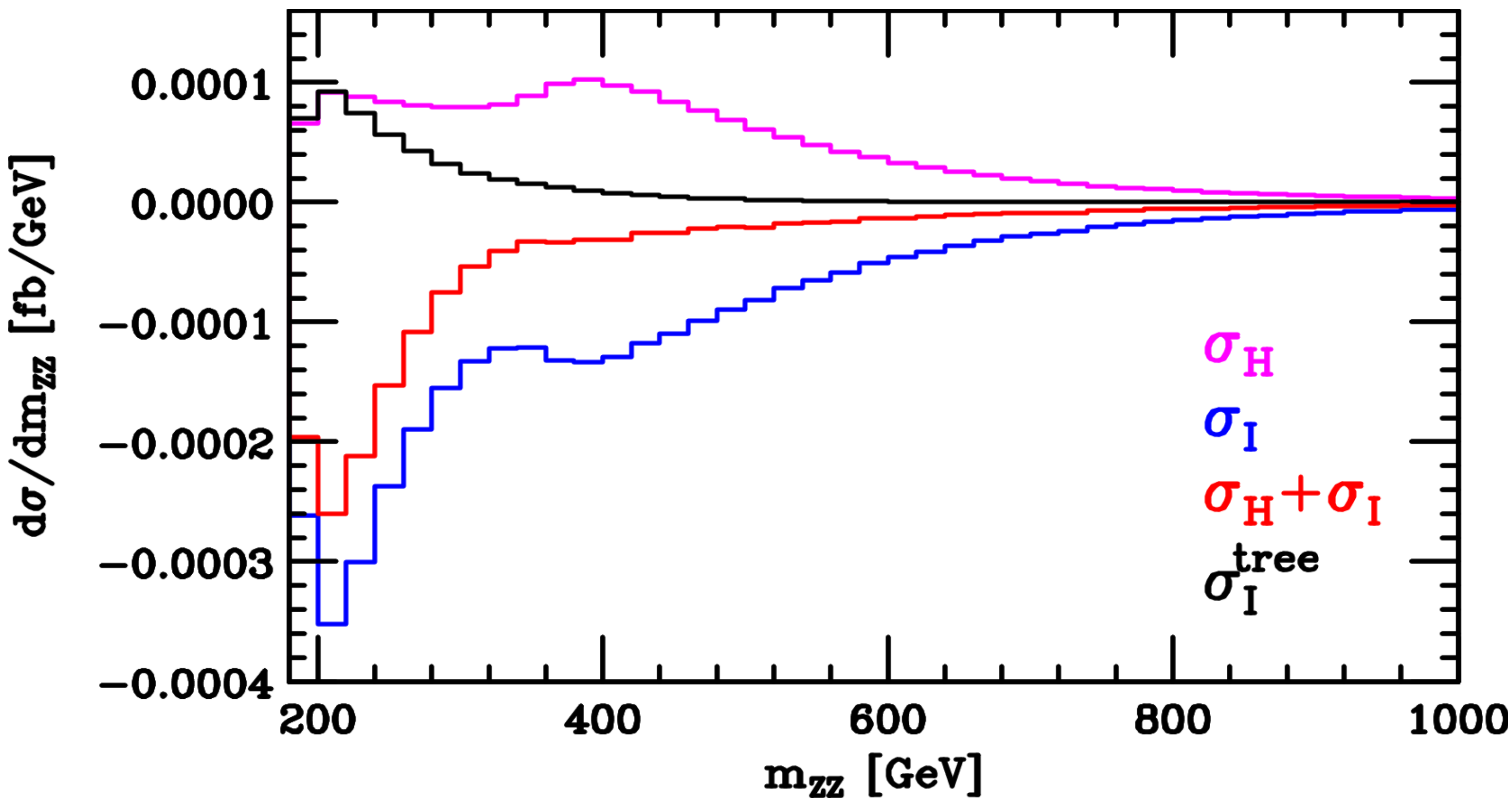
- Quark-initiated contributions amount to **25-50%** at 8 TeV, smaller at 13 TeV.
- “Loop” interference contributions are large and negative (req'd by unitarity).
- “Tree” interference are small.

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.
- **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



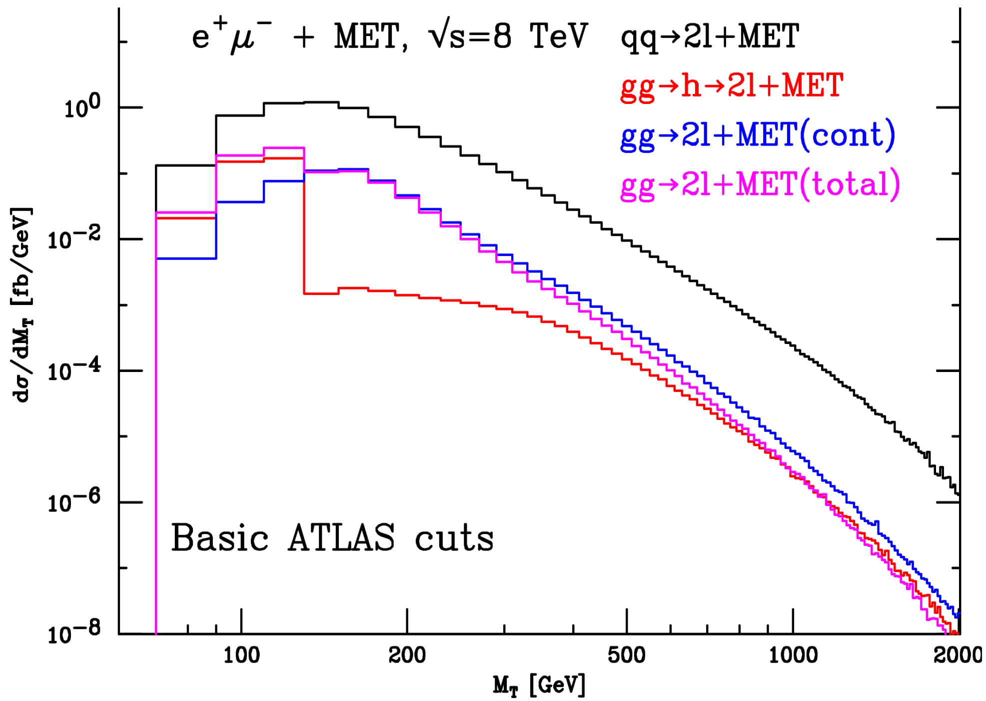
- Interference has dramatic effect on shape as well as normalization.

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: $$\sigma_{\rm off} = 0.0280 \frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 0.0392 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$
- Expect comparable width constraints in 1-jet bin

High mass tail in H → WW

- Similar pattern of high-mass behavior in H → WW.
- Mass reconstruction not possible
  - Use transverse mass mT
- On-shell mT < mH – easy separation into on-shell and off-shell regions



- Higgs off-shell cross section smaller than in H → ZZ, interference dominates
- Typical expt cuts dramatically reduce off-shell cross sections

Width constraints from H → WW

- Expected constraints on Higgs width: $\Gamma_H \leq 45\ \Gamma_H^{\rm SM}$
  - Uses mT > 300 GeV for high-mass region
  - “Basic” ATLAS cuts
- Require jet veto to remove large top-pair background
- This introduces **large logarithms** – require resummation (Moult and Stewart, hep-ph/1405.5534)
- Weaken width constraint by factor of 2

Theoretical control

- Return to H → ZZ [same issues for H → WW]
- 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.
- Valid in SM → consistency check of SM parameter
- 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

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

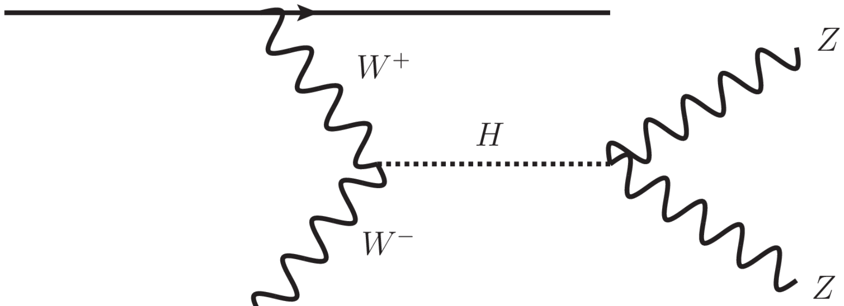
  the interpretation as a width constraint is **valid**.
- Examples: Dimension-6 extension of Higgs sector with Higgs portal, minimal extension of Higgs sector.
- Not valid for, e.g. MSSM

Model independence

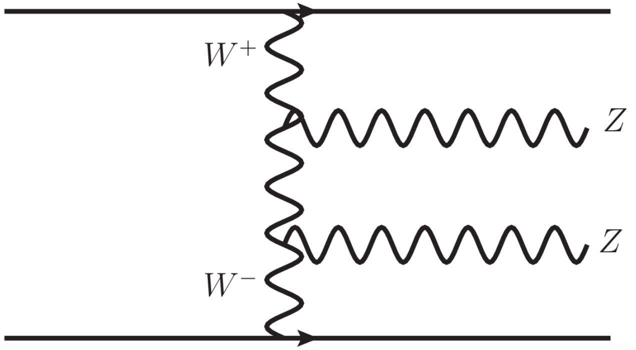
- Even when constraint on Higgs width **not** a valid interpretation, off-shell Higgs behavior is important:
  - Constrain off-shell couplings
  - Probe loop for new particles (e.g. light stops)
  - Check on unitarizing action of Higg mechanism

Interference effects in VBF H → ZZ

- Again, Higgs amplitudes (a) required to cancel high-energy behavior of longitudinal modes [e.g. in (b)]
- So expect similar pattern in high mass tail:
  - "Signal" and "background" cross sections large
  - But strong destructive interference
  - Constraints on Higgs width possible
    - Perturbative convergence better?
    - Model independence more straighforward?



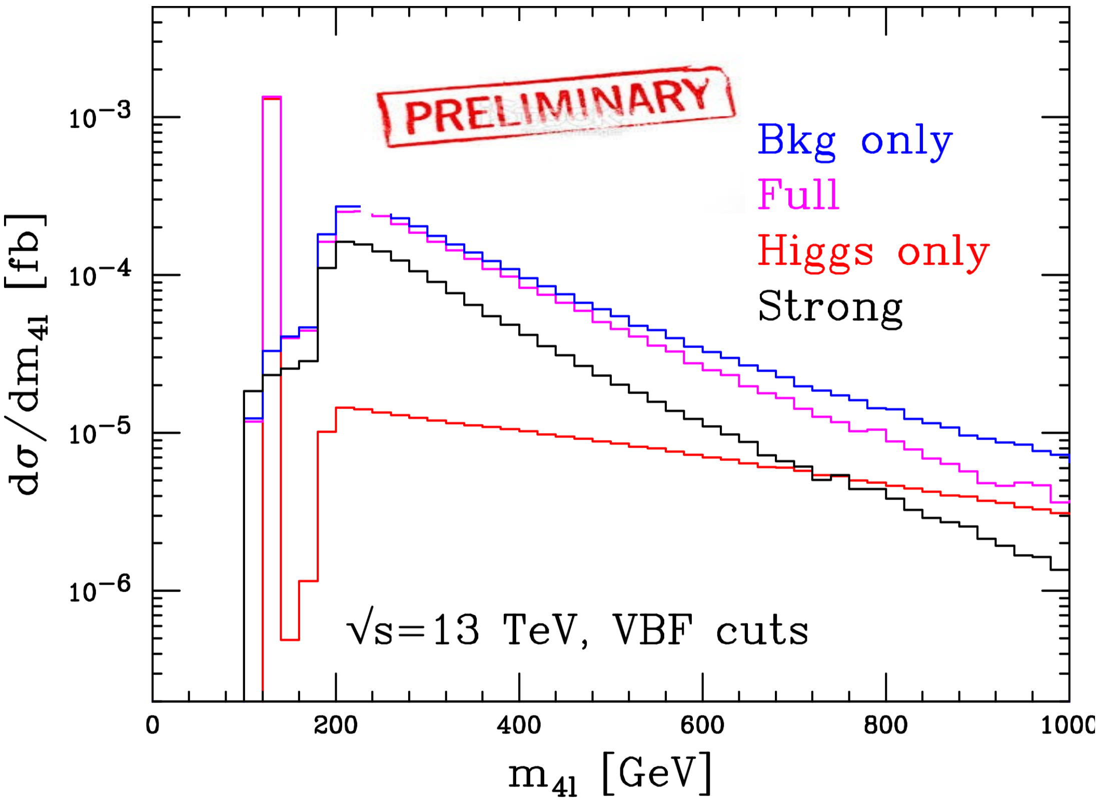
(a)



(b)

Interference in VBF H → ZZ : Preliminary Results

- Effect of interference very clear – rapid drop of full result as compared to Higgs only
- Strong background reduced by VBF cuts
- **~10% of rate** in high mass tail



Courtesy J. Campbell and R.K. Ellis

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)

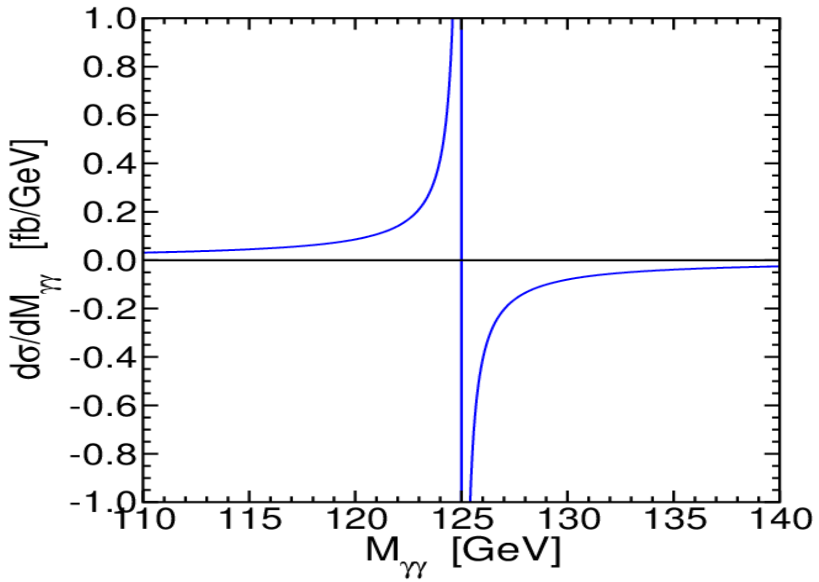
    (Dixon, Siu, hep-ph/0302233)

  - 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

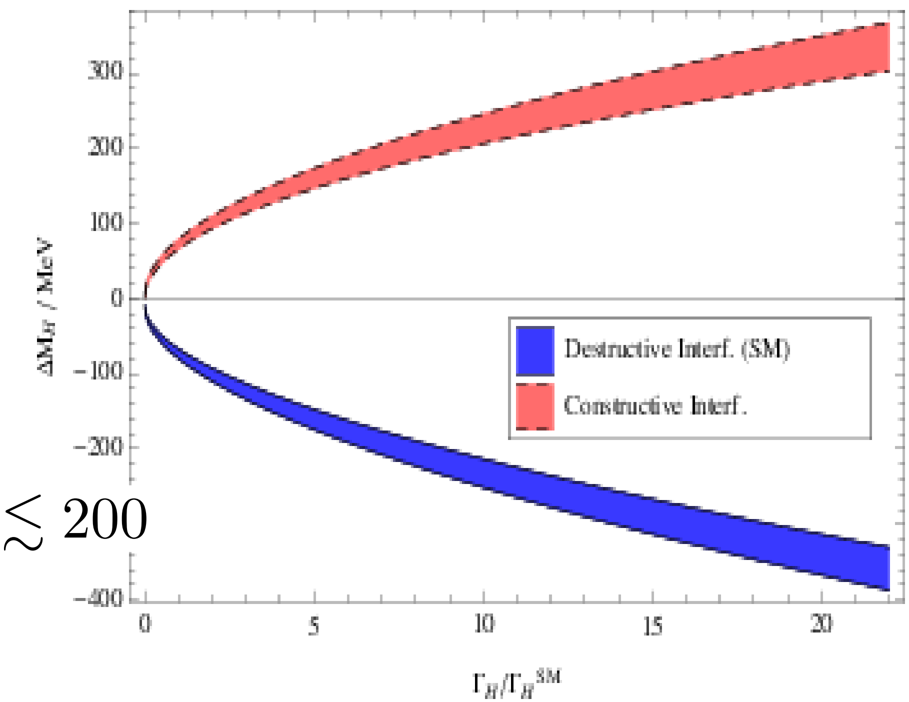
Bounding Higgs Width with Mass Peak Shift

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

~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)

Conclusions

- High-mass behavior of Higgs governed by requirements to unitarize amplitudes with longitudinal gauge bosons:
  - Significant fraction of rate in far off-shell region
  - Large interference between “signal” and “background”
- Effects shown in GF H → ZZ, GF H (→ ZZ)+jet, GF H → WW, VBF H → ZZ
- Can be used to measure/constrain off-shell couplings/Higgs width

  $$\Gamma_H \lesssim \mathcal{O}(10-100)\Gamma_H^{\rm SM}$$
- Much still to be done:
  - Higher order corrections
  - Model independence
  - VBF
  - Other production/decay modes
  - ….

THANK YOU!

Backup: Higgs Width from Coupling Fits

- Another indirect method: Use coupling data to constrain Higgs width
- Theoretically well-motivated assumption

  $|C_{Z,W}| < 1.0$ (could go to 1.3)

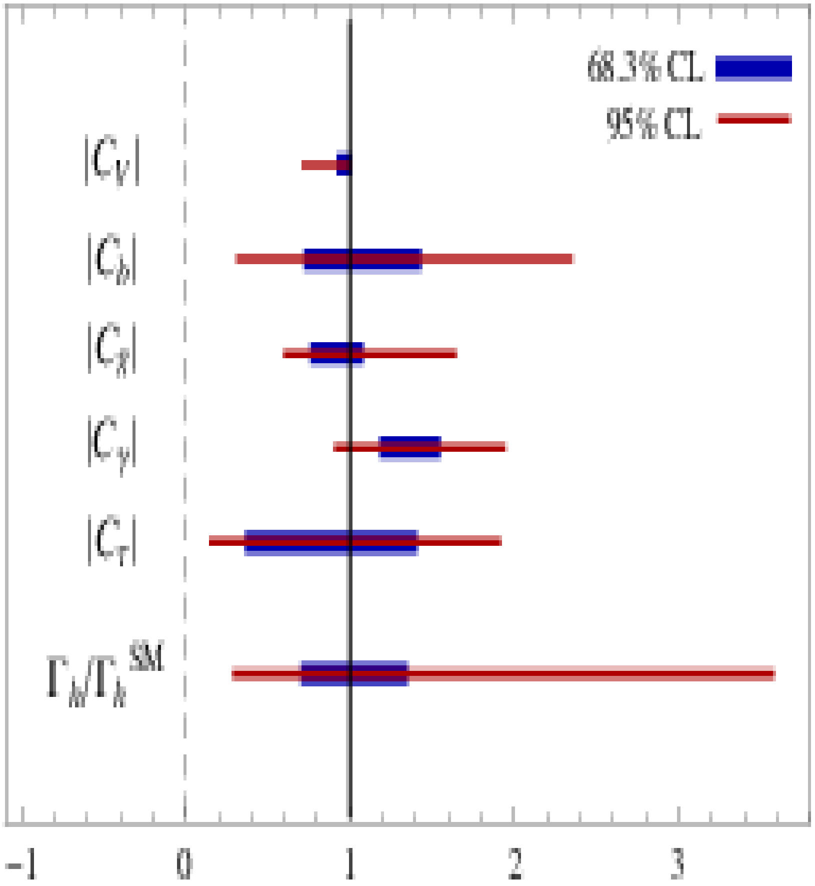
- Higgs coupling fits to *WW, ZZ, γγ, bb, gg, ττ*

  → Upper bound on Higgs width

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

  (Dobrescu, Lykken, hep-ph/1210.3342)

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



Backup: Higgs Width from Coupling Fits

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

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

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

- Very good limits
- Cons:
  - Model dependence/theoretical assumptions?
  - Black box