Higgs off-shell couplings and width

Berlin, 11 September 2014

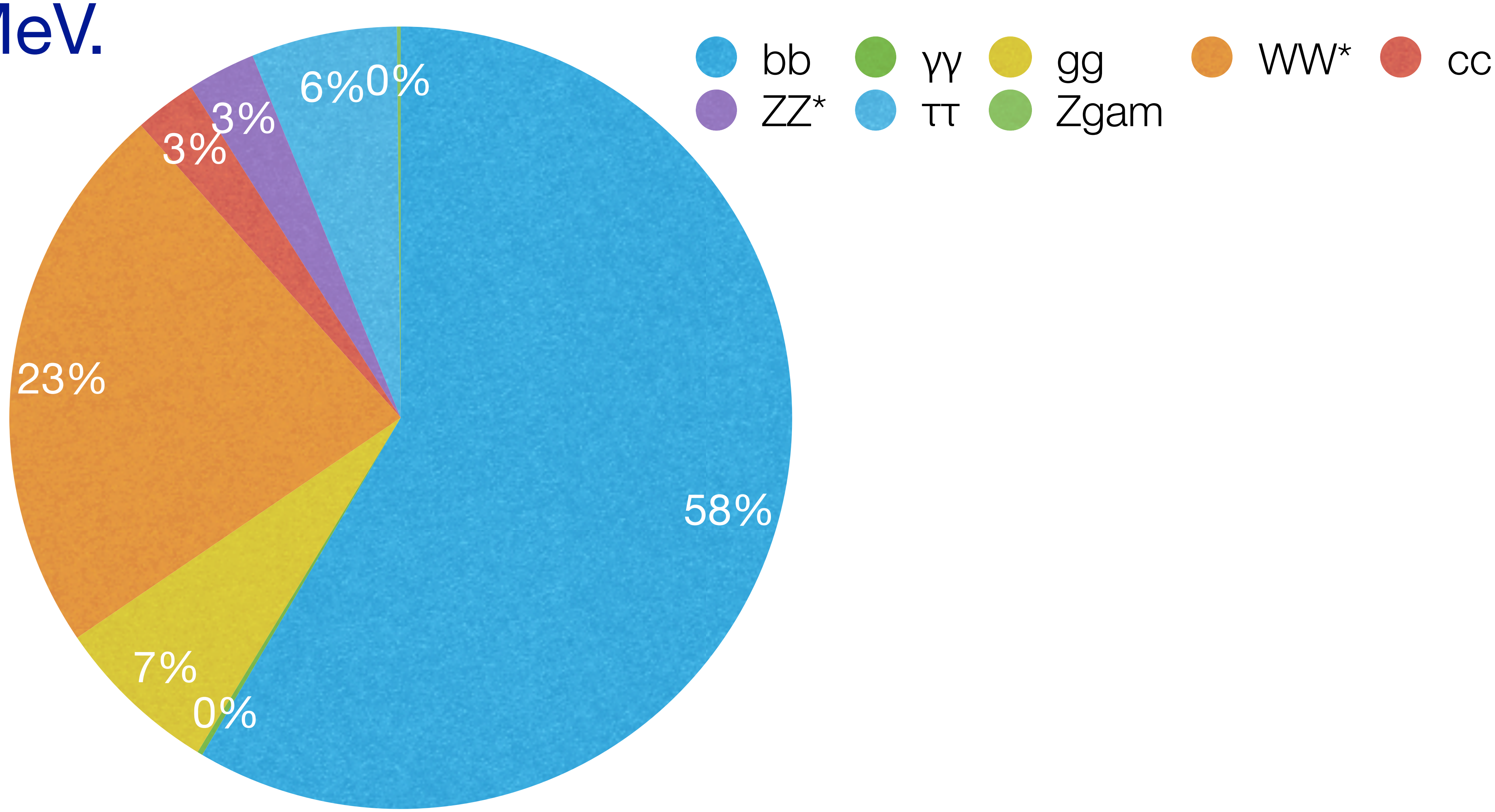
Keith Ellis, Fermilab

- Line shape studies in $\gamma\gamma$
- $ZZ^{(*)} \rightarrow 4$ leptons
- Interference in ZZ+jet

Campbell, Ellis,Williams, 1311.3589
Campbell, Ellis,Furlan,Rontsch, 1409.1897

Higgs boson branching fractions

- Large number of observable SM Higgs decays
- We will consider ɣɣ,ZZ*.
- ZZ* is 3%, before BR to observable mode.
- $\Gamma_H^{SM} \approx 4$ MeV.



Higgs width — Higgs lifetime

- How can we probe a SM width of 4 MeV at the LHC?
- Intrinsic detector resolution is of order a few GeV in most well-measured channels
- Direct limits are therefore inherently weak.
- The observed (expected) upper limit is found to be 6.9(5.9) GeV at 95% confidence level. (CMS PAS-HIG-13-016)
- This corresponds to $\Gamma_H < 1600\ \Gamma_H^{SM}$

Particle	Width[MeV]	Lifetime[s]
t	$\sim 1,300$	$\sim 5 \times 10^{-25}$
W	$\sim 2,000$	$\sim 3 \times 10^{-25}$
Z	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
h	4.21 ± 0.16	$\sim 1.65 \times 10^{-22}$
b	4.4×10^{-10}	$\sim 1.5 \times 10^{-12}$

Interference effects in γγ

Dixon-Siu hep/ph0302233

- Resonance-continuum interference effects are normally small for a narrow resonance.
- γγ production amplitude is a sum of Higgs mediated and continuum diagrams.

$$\mathcal{A}_{gg\to\gamma\gamma} = -\frac{\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}}{\hat{s}-m_H^2+im_H\Gamma_H} + \mathcal{A}_{cont}$$

- The interference term can be written as a sum of 2 terms:

$$-2(\hat{s}-m_H^2)\frac{Re(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{cont})}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}$$

- averages to zero, shifts apparent mass

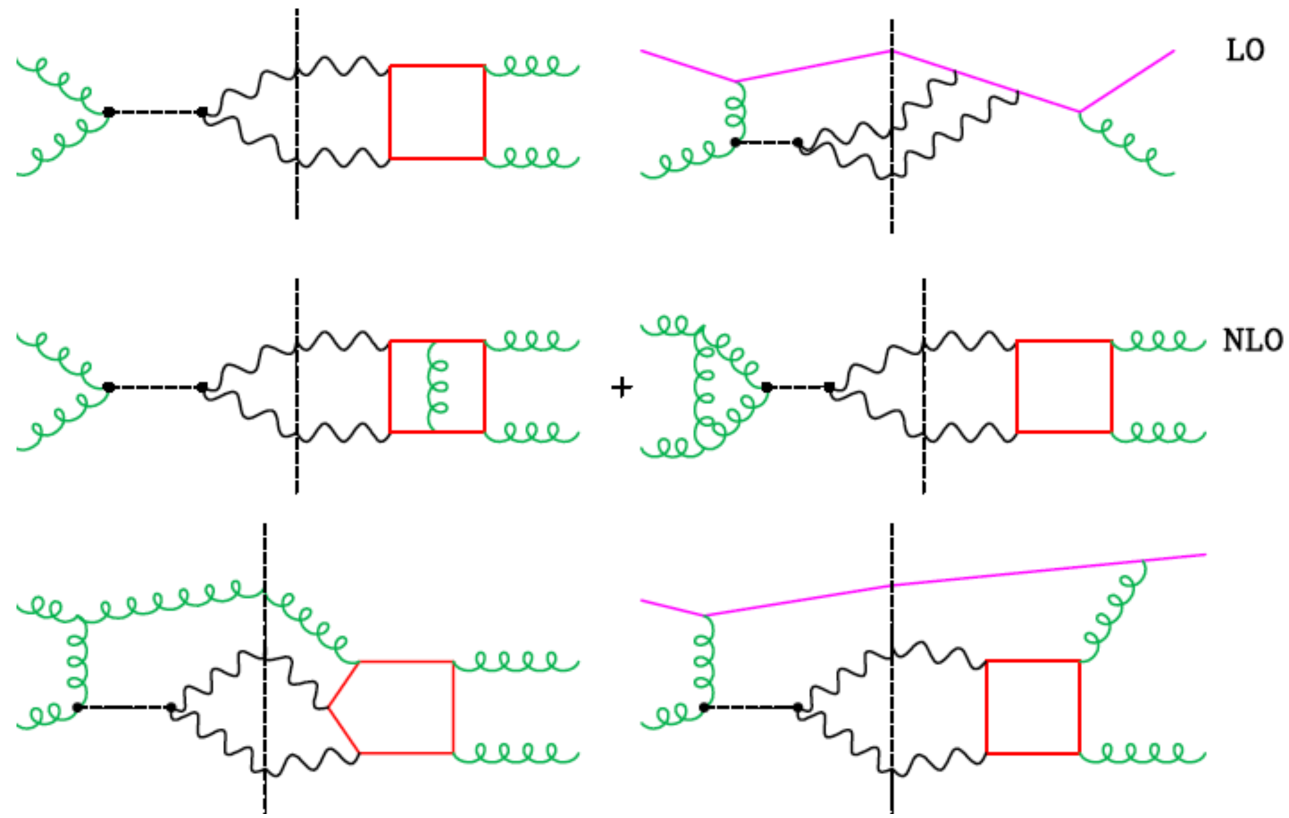
$$-2m_H\Gamma_H\frac{Im(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{cont})}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}$$

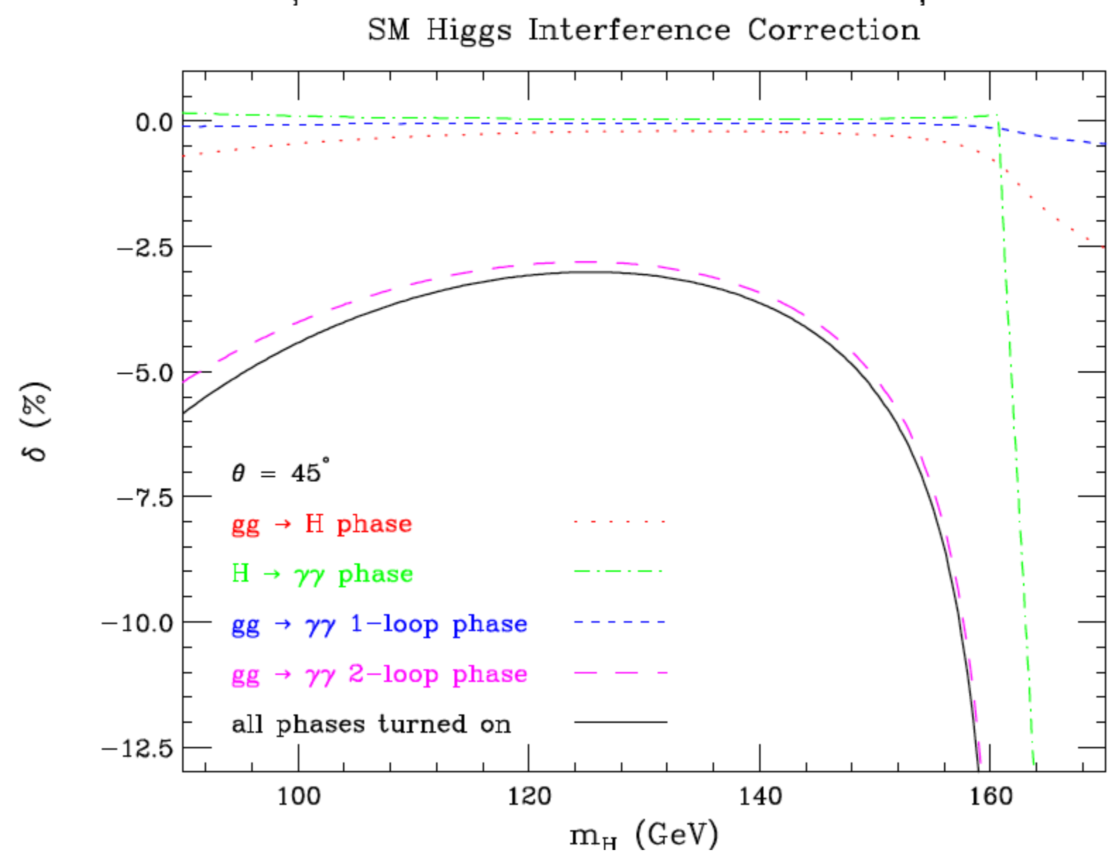
- changes peak height

- Experimental resolution averages over line-shape.

Interference effects in $\gamma\gamma$ (imaginary part)

- One-loop contribution vanishes for $m_q \to 0$ because of helicity suppression for like helicities.
- Dominant term comes from two loops.
- Interference is destructive and of order 5%.

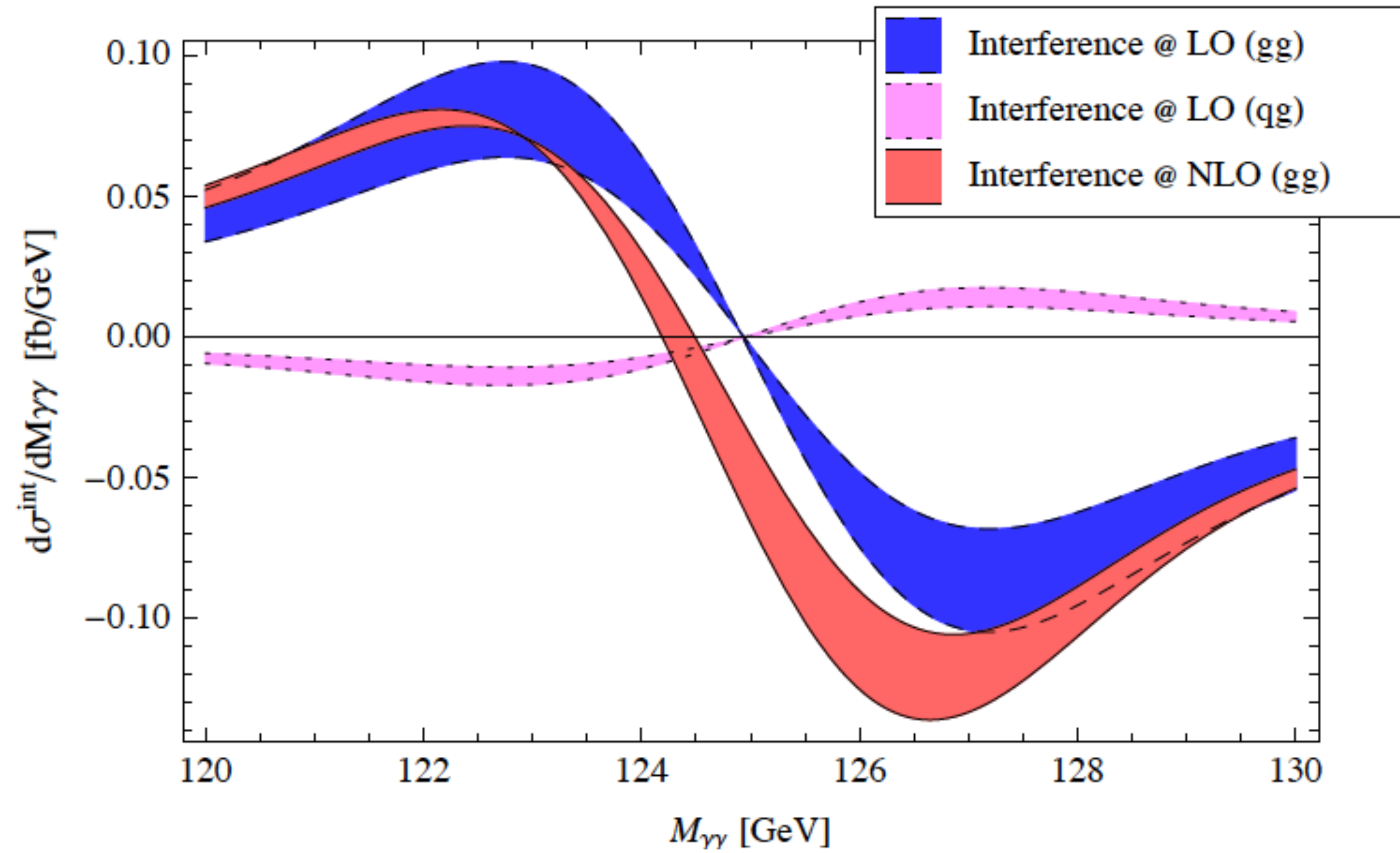




Interference effects in γγ (real part)

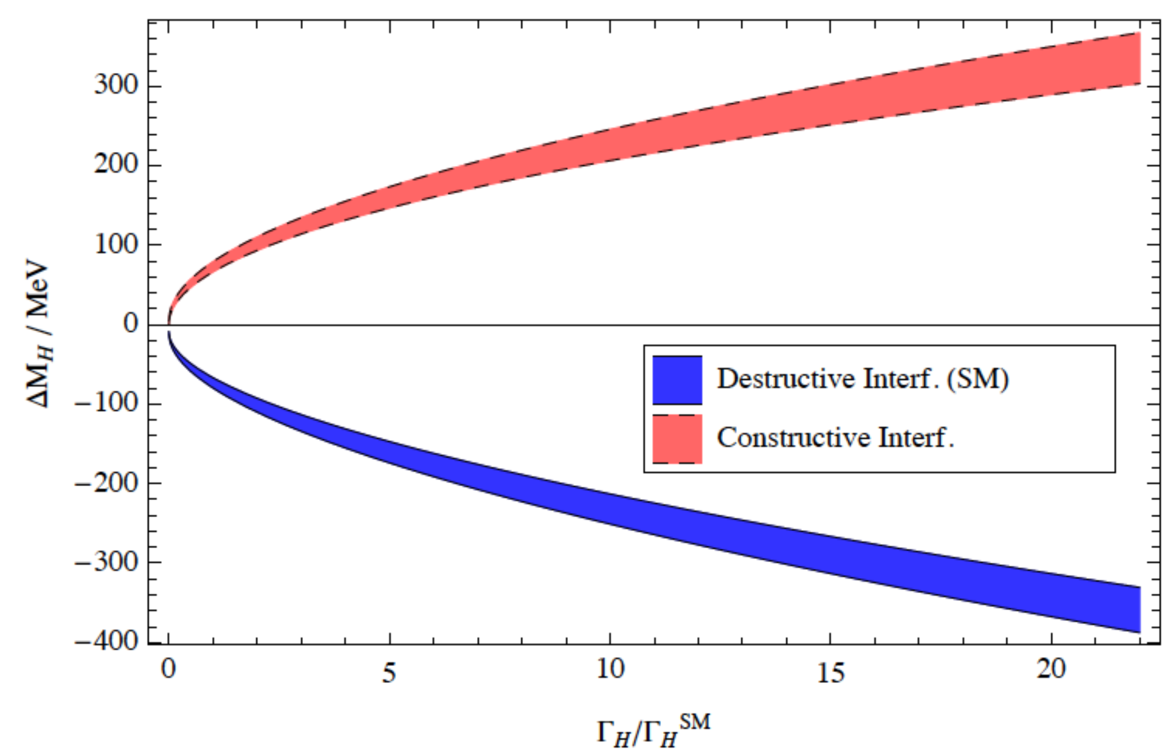
Martin 1208.1533,1303.3342
de Florian et al, 1303.1397
Dixon-Li 1305.3854

- Gaussian smeared interference contribution, (σ=1.7GeV)
- Apparent mass shift for inclusive production at NLO is about 70MeV
- Significantly less than LO≃120MeV.
- Needs to be repeated with real experimental resolution.
- Tool available?



Current data: using the Z as a reference mass

- Current limits problematic because experiments do not agree on the sign of shift, but notionally the current sensitivity assuming a 1 GeV mass shift is of order $200\Gamma_{SM}$
- ATLAS: $m_H^{\gamma\gamma} - m_H^{4l} = +1.47 \pm 0.72$ GeV arXiv:1406.3827
- CMS: $m_H^{\gamma\gamma} - m_H^{4l} = -\,0.87^{+0.54}_{-0.59}$ GeV CMS-PAS_HIG-14-009
- Ultimately with $3ab^{-1}$ one can achieve $\Delta m_H \sim 100$MeV, leading to a bound of $15\Gamma_{SM}$ at 95%cl.

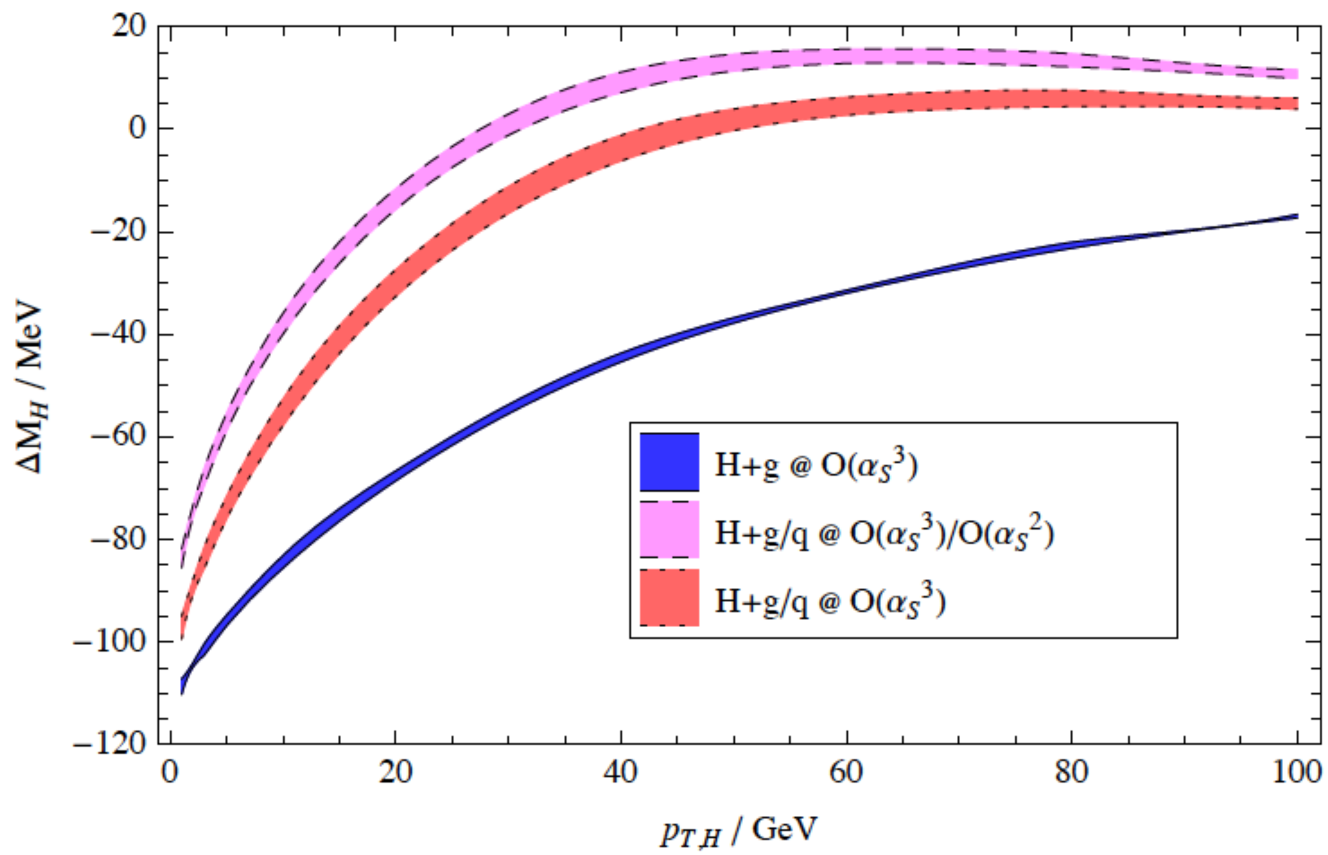


Dixon-Li 1305.3854

Reference masses

* ZZ(4l lepton) mass, (M_{ZZ} mass shift negligible)
* ɣɣ mass at high p_T :with a cut at ~30GeV, there is no mass shift.

Martin 1303.3342, Dixon-Li 1305.3854



* ɣɣ mass in vector boson fusion

Line-shape in $ZZ^{(*)}$

Narrow width approximation for Higgs production

- In the limit $\Gamma/M_h \rightarrow 0$ we may replace the Breit-Wigner distribution by a delta function.

$$\frac{1}{(\hat{s} - M_h^2)^2 + M_h^2 \Gamma_h^2} \approx \frac{\pi}{M_h \Gamma_h} \delta(\hat{s} - M_h^2) \ .$$

- For the standard model Higgs, $\Gamma/M_h = 1/30{,}000$ so narrow width approximation should apply.

Rescaling properties of the cross section on the peak

- In the narrow width approximation

$$\sigma(i \to H) \times BR(H \to X) = |M(i \to h)|^2 \frac{\Gamma(h \to X)}{\Gamma_h} \sim \frac{g_i^2 g_f^2}{\Gamma_h}$$

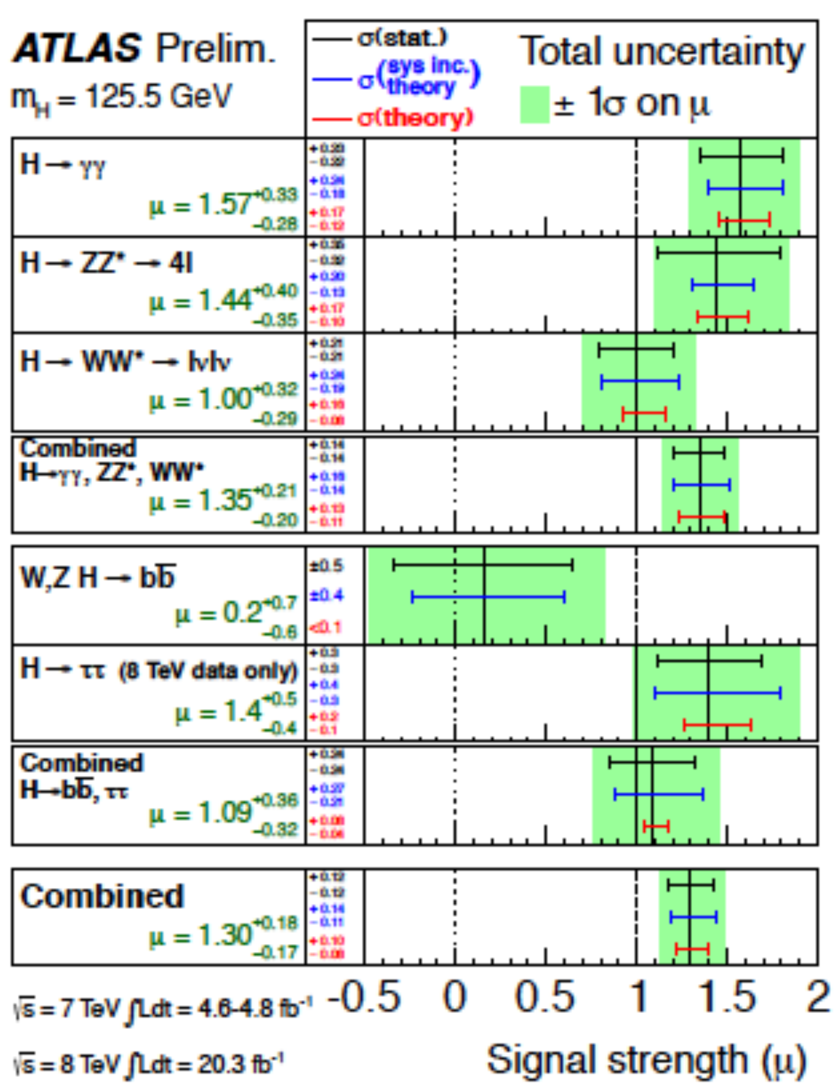
- Measurements on the Higgs peak, are only sensitive to the ratio, $\dfrac{g_i^2 g_f^2}{\Gamma_h}$

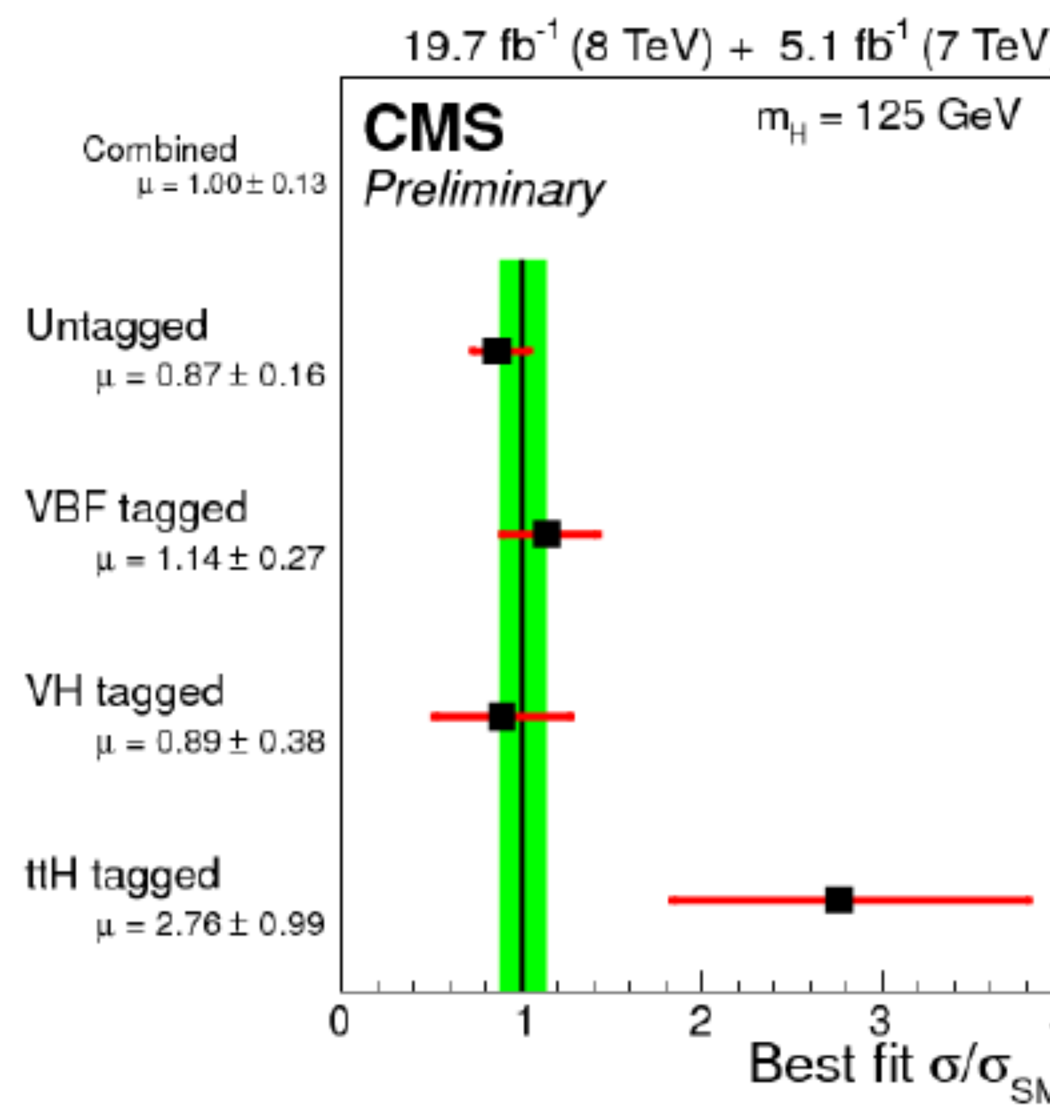
- Performing the rescaling by ξ leaves the measurement unchanged.

$$\begin{aligned} g_i &\to \xi g_i \\ g_f &\to \xi g_f \\ \Gamma_H &\to \xi^4 \Gamma_H \end{aligned}$$

Signal strength measurements

- Signal strength measurements, (that assume a value for the total width), confirm that $g_i^2 g_f^2/\Gamma_h$ is close to its standard model value (with errors > 20%)





Basic process for line shape in ZZ: pp→ZZ→$e^-e^+\mu^-\mu^+$

$$
\begin{array}{l}
p + p \to H \to ZZ \\
\qquad\qquad\qquad\quad \hookrightarrow \mu^- + \mu^+ \\
\qquad\qquad\qquad \hookrightarrow e^- + e^+ \, .
\end{array}
$$

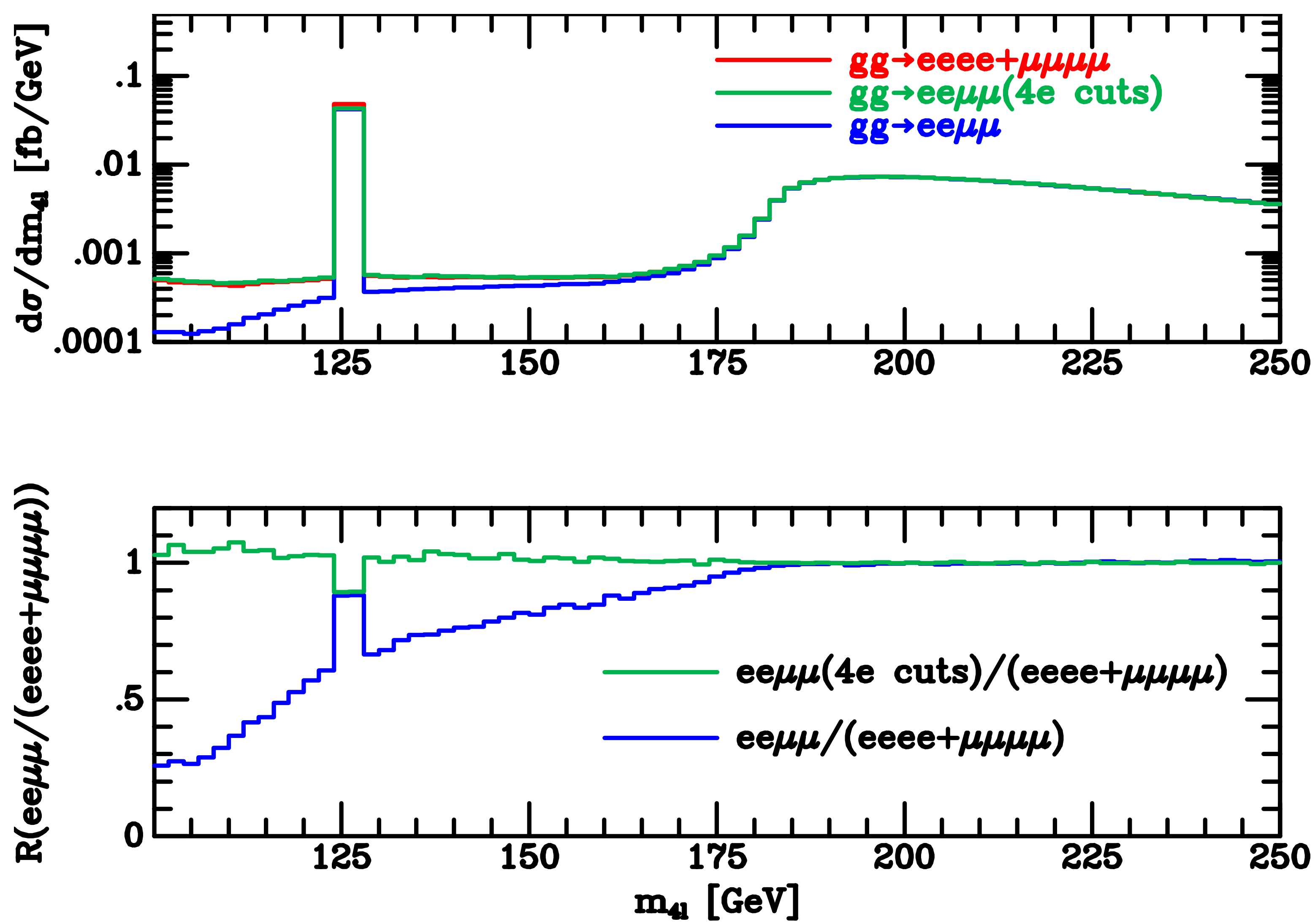
$$
\begin{array}{l}
p + p \to Z/\gamma^* + Z/\gamma^* \\
\qquad\qquad\qquad\qquad \hookrightarrow \mu^- + \mu^+ \\
\qquad\qquad \hookrightarrow e^- + e^+
\end{array}
$$

- Consider the contributing Feynman diagrams.

Technically, only non-identical fermions although identical fermion effects are known to be small away from the Higgs resonance.

Interference effects in gg processes

- Cross sections can differ for distinguishable particles, because of the one less combination which can be restricted to the region around the Z.
- Applying identical cuts we see that the effect of identical vs distinguishable particles is small, except at the Higgs peak.
- At the peak the (4e+4μ) rate is larger than the 2e2μ rate.
- Included in MCFM6.8

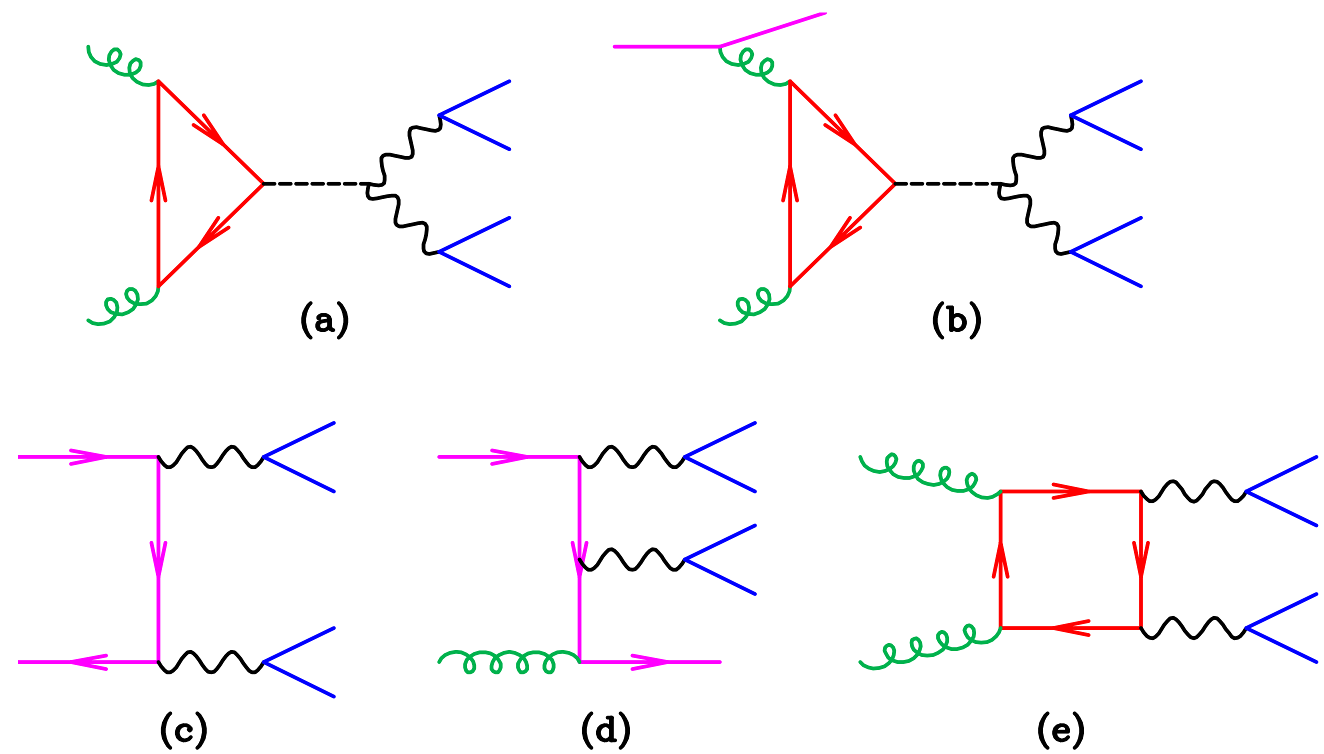


pp→$e^-e^+\mu^-\mu^+$ in the standard model

- Mishmash of orders in perturbation theory

$(a) : g(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(b) : q(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s^3 e^4)$
$(c) : q(-p_1) + \bar{q}(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(e^4)$
$(d) : q(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s e^4)$
$(e) : g(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$

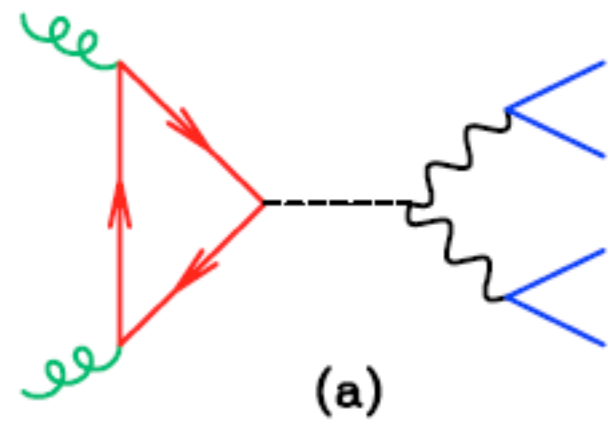
- Representative diagrams are:-



- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e) see later.

Narrow width approximation for Higgs boson

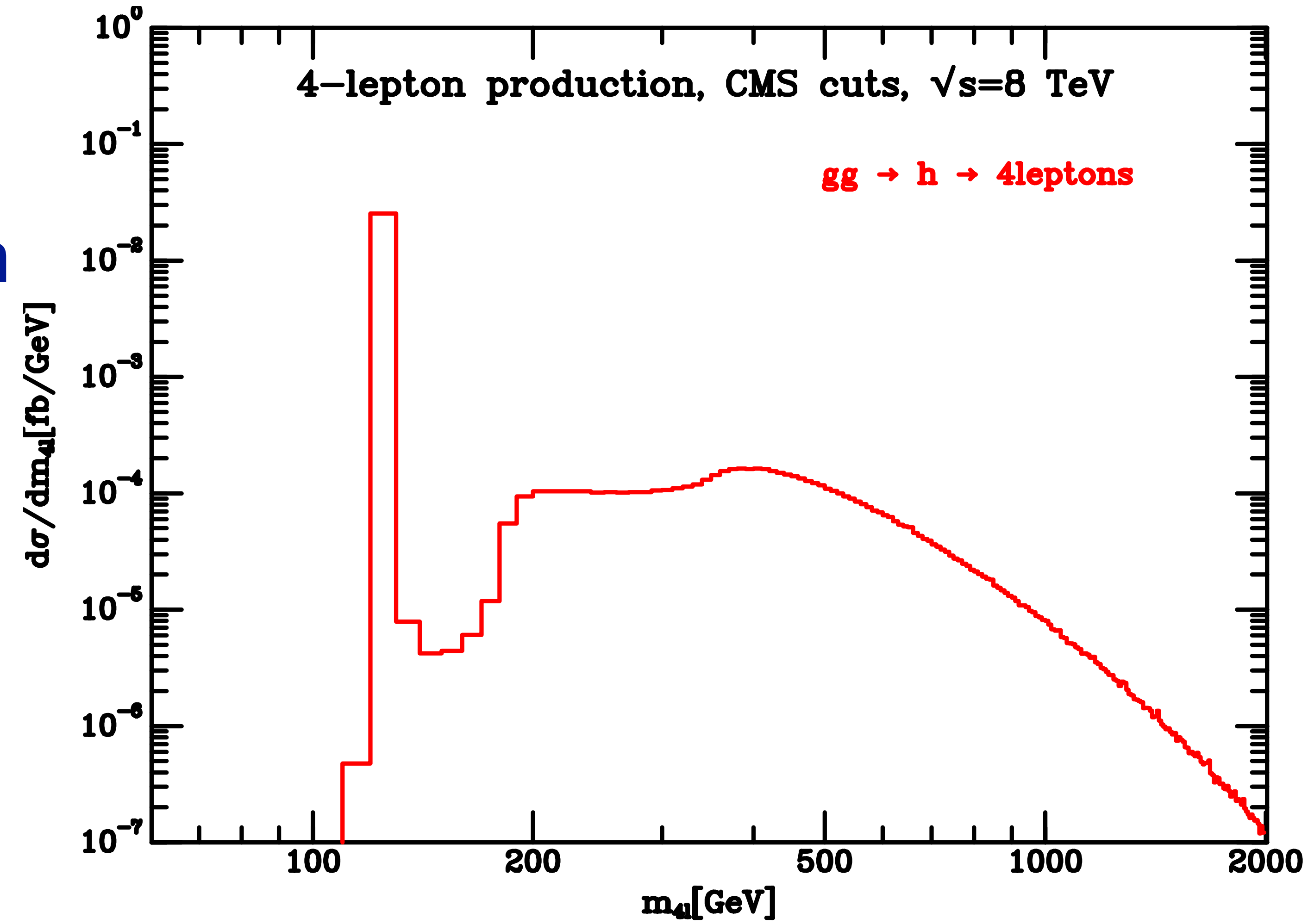
- How can it fail?
  - $\Gamma_H / M_H = 1/30{,}000$



- It fails spectacularly for $gg \to H \to ZZ^{(*)} \to e^- e^+ \mu^- \mu^+$.

- At least 10% of the cross section comes from $m_{4l} > 130$GeV.

  Kauer, Passarino,arXiv:1206.4803



- 3 phenomena happening in the tail.

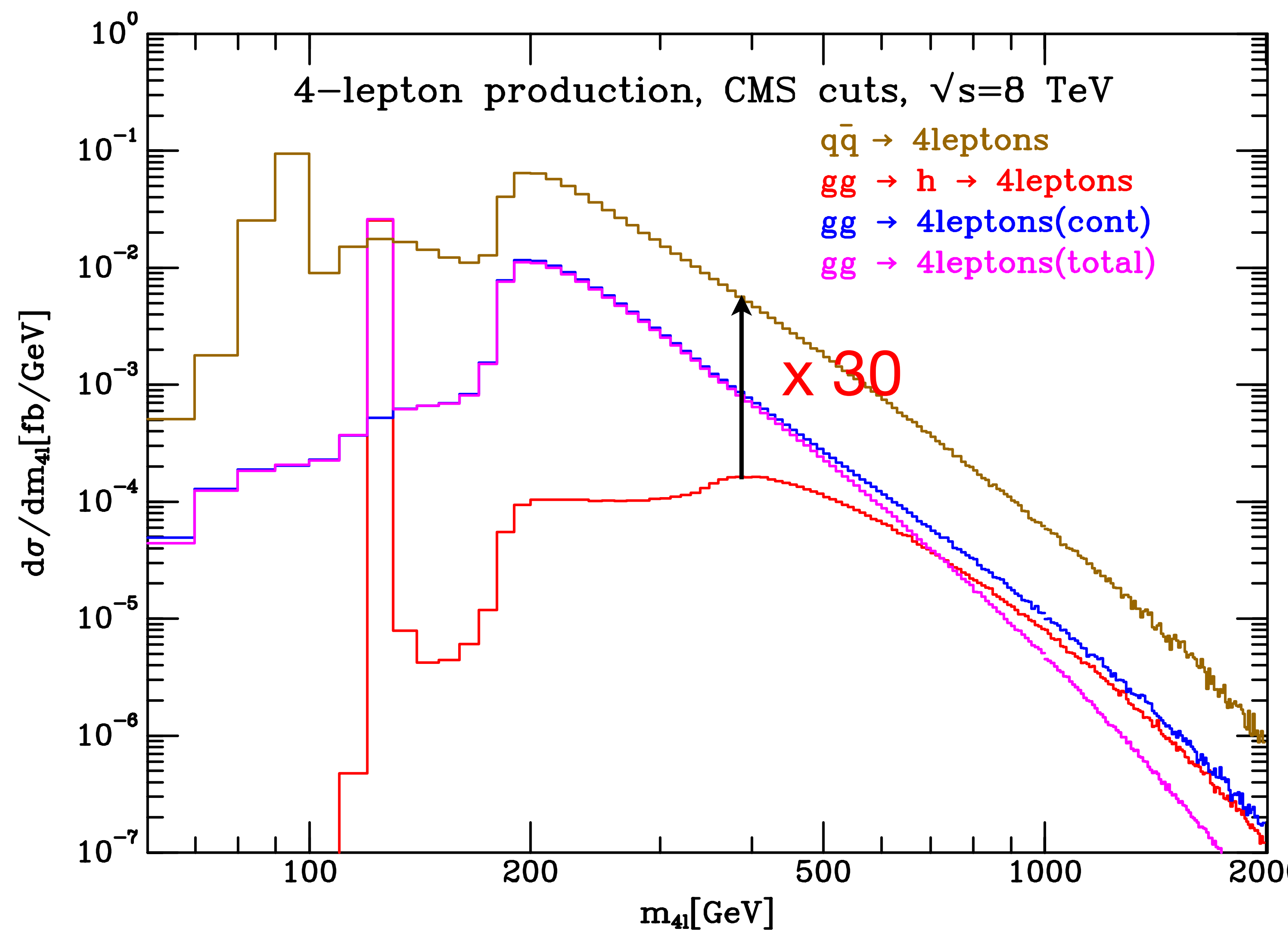
- Similar tail for $H \to WW$.

The big picture @ 8TeV

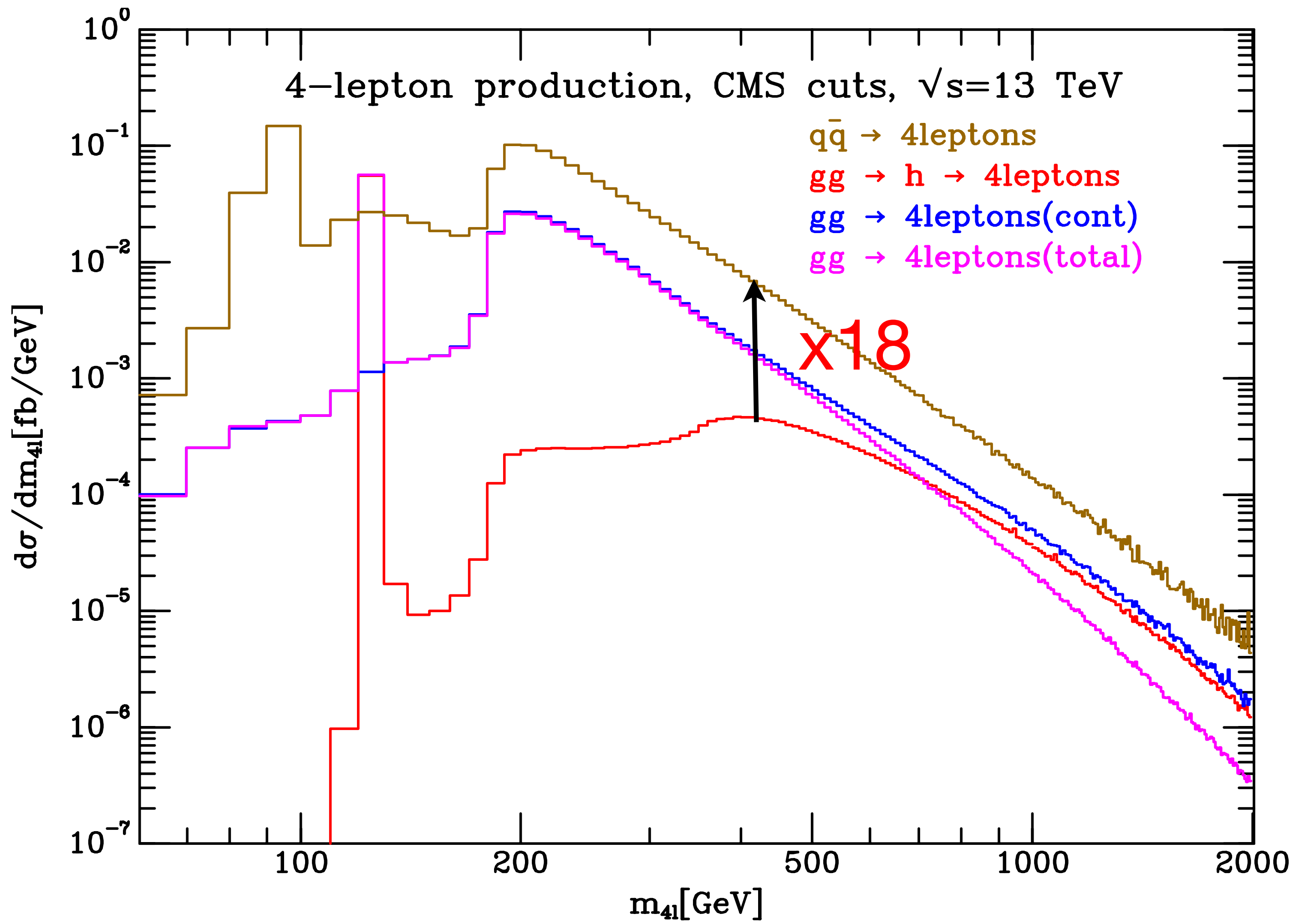
- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width, Γ_H, challenging to see enhancement/deficit due to Higgs channel.

$$p_{T,\mu} > 5 \text{ GeV}\,, \quad |\eta_\mu| < 2.4\,,$$
$$p_{T,e} > 7 \text{ GeV}\,, \quad |\eta_e| < 2.5\,,$$
$$m_{ll} > 4 \text{ GeV}\,, \quad m_{4\ell} > 100 \text{ GeV}\,.$$

CMS cuts
CMS PAS HIG-13-002



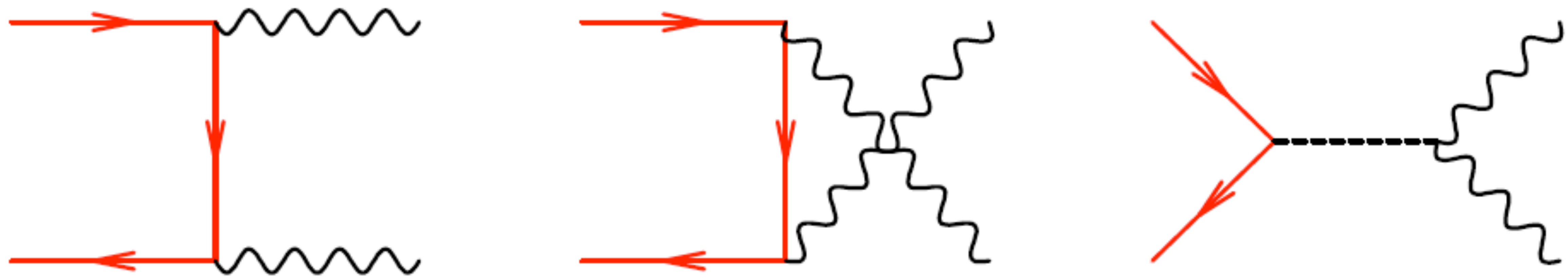
The big picture @ 13 TeV



- σ_{qqb} (m_{4l}=400)/$\sigma^{H}{}_{gg}$ (m_{4l}=400) ≈ 18 at $\sqrt{s}$=13 TeV
- (c.f. ~30 at $\sqrt{s}$=8 TeV).
- Higgs off-shell contribution is relatively bigger at higher energy.

Higgs being Higgs

- Consider right hand side of gluon-gluon initiated diagrams.
- tt → ZZ, longitudinal modes of Z-bosons.

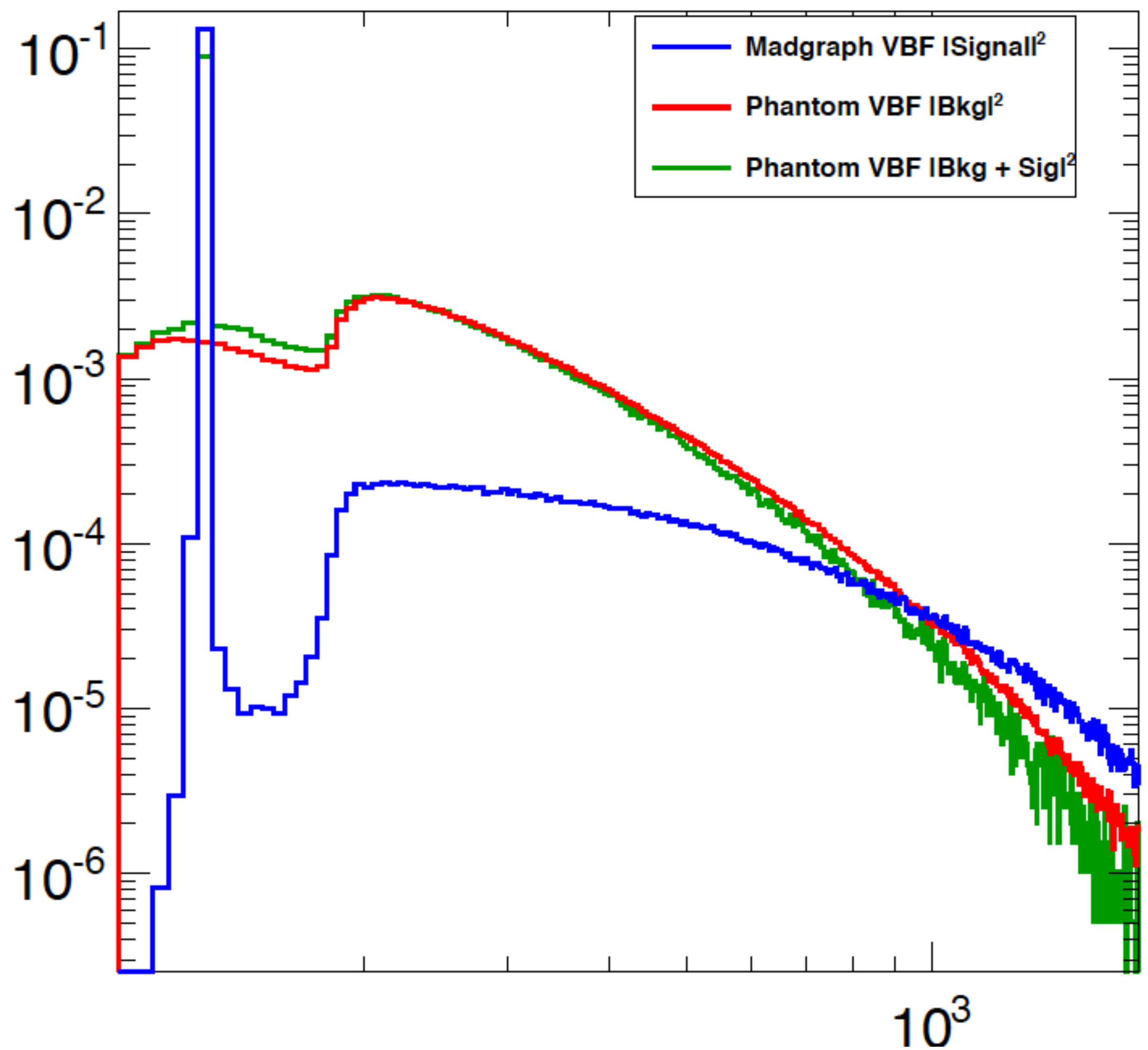


$a_2E^2+(b_1+a_1)m_tE$ $\quad$ $-a_2E^2+(c_1-a_1)m_tE$ $\quad$ $-(b_1+c_1)\ m_tE$

- Higgs tail has to be there to cancel bad high energy behavior of continuum diagrams.
- Observation of this cancellation, (if possible) is as interesting as longitudinal WW,ZZ scattering.

Similar tail in vector-boson fusion production

- pp -> jet+jet+$e^-e^+\mu^-\mu^+$



Passarino, Loops and Legs, April 2014

Caola-Melnikov method for Higgs width

- Higgs cross under the peak, section depends ratio of couplings and width.

$$\sigma_{\text{peak}} \propto \frac{g_i^2 g_f^2}{\Gamma}$$

- Measurements at the peak cannot untangle couplings and width.

- Off-peak cross section is independent of the width, but still depends on $g_i^2 g_f^2$ (modulo interference, see later).

$$\sigma_{\text{off}} \propto g_i^2 g_f^2$$

- Taking ratio

$$\frac{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{experimental gg}}}{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{theoretical SM}}} = \frac{\Gamma}{\Gamma^{\text{SM}}}$$

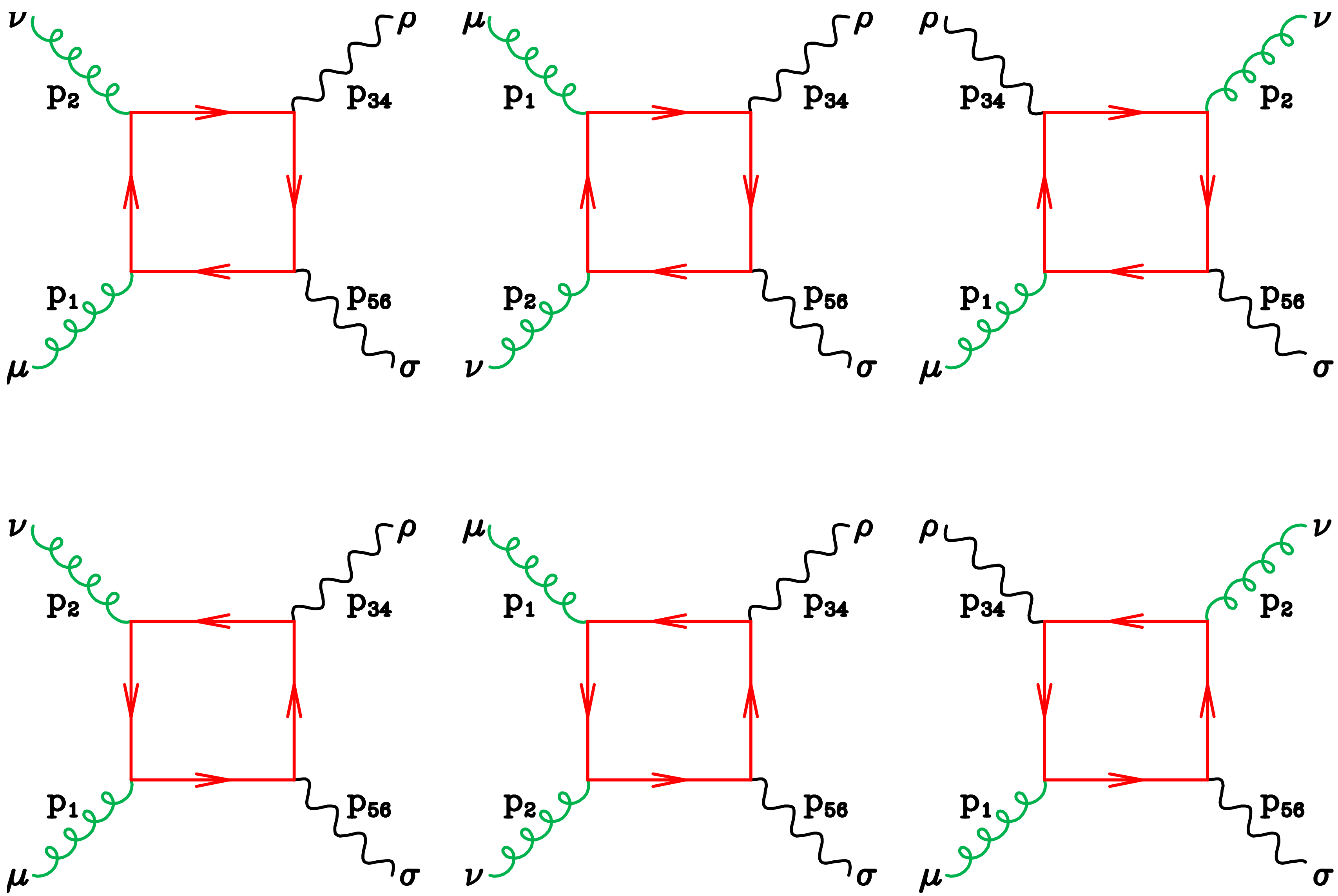
- Ratio depends linearly on the Higgs boson width.

Caola-Melnikov 1307.4935

Caola-Melnikov method

* Although the interference has to be there, it is not essential for the CM method.
* Destructive interference actually weakens the bound that is obtained.
* CM method relies on accurate theoretical values for 4-charged lepton cross section (including the interference) both on and off-peak.
* the CM method requires that the measured off-shell couplings are the same as the on-shell couplings.
* It is a pragmatic approach, utilizing the experimental information at hand.

Diagrams for gg→Z/g*+Z/g* (background)



* Classify by the chirality of coupling to Z, i.e. VV or (AA-VV).

History: $gg \to ZZ \to e^- e^+ \mu^- \mu^+$

- Calculation requires VV or AA piece.
- VV piece first calculated in 1950, Karplus-Neuman Phys Rev 83 776 (1951)
- VV piece re-calculated in 1971, dispersive technique
  Constantini, de Tollis, Pistoni Nuovo Cim A2 1971
- (AA-VV) piece calculated for on-shell Z's, (inadequate for year>2012 purposes) Glover and van der Bij NPB321 (1989)
- Extension to off-shell Z's (no analytic formula for VV) Zecher et al, hep-ph/9404295
- gg2VV code, Kauer and Passarino, 1206.4803
- No published analytic form for the VV piece since 1971.
- Our aim: to obtain fast, stable code, to include in MCFM, using modern methods. Publish formula with value at a given phase space point, so it is feasible for other authors to implement. Campbell, Ellis, Williams 1311.3589

Expression for Continuum amplitude

- (Slight) generalization of integral basis to aid with numerical stability

$$A = \sum_{j=2}^{3} d_j(1^{h_1}, 2^{h_2})\, D_0^{d=6}(j) + \sum_{j=1}^{3} d_j(1^{h_1}, 2^{h_2})\, D_0(j)$$
$$+ \sum_{j=1}^{6} c_j(1^{h_1}, 2^{h_2})\, C_0(j) + \sum_{j=1}^{6} b_j(1^{h_1}, 2^{h_2})\, B_0(j) + R(1^{h_1}, 2^{h_2})$$

- Complete analytic forms for integral coefficients in terms of spinor products, e.g.

$$d_2^{d=6}(1^-, 2^+) = \frac{-1}{[3\,4]\langle 5\,6\rangle s_{134}} \frac{\langle 1|(3+4)|2]}{\langle 2|(3+4)|1]^3} \left[\langle 2|(1+3)|4]^2 \langle 5|(3+4)|1]^2 + s_{134}^2 \langle 2\,5\rangle^2 [1\,4]^2\right]$$

- Relatively simple formulae for each presented in paper.

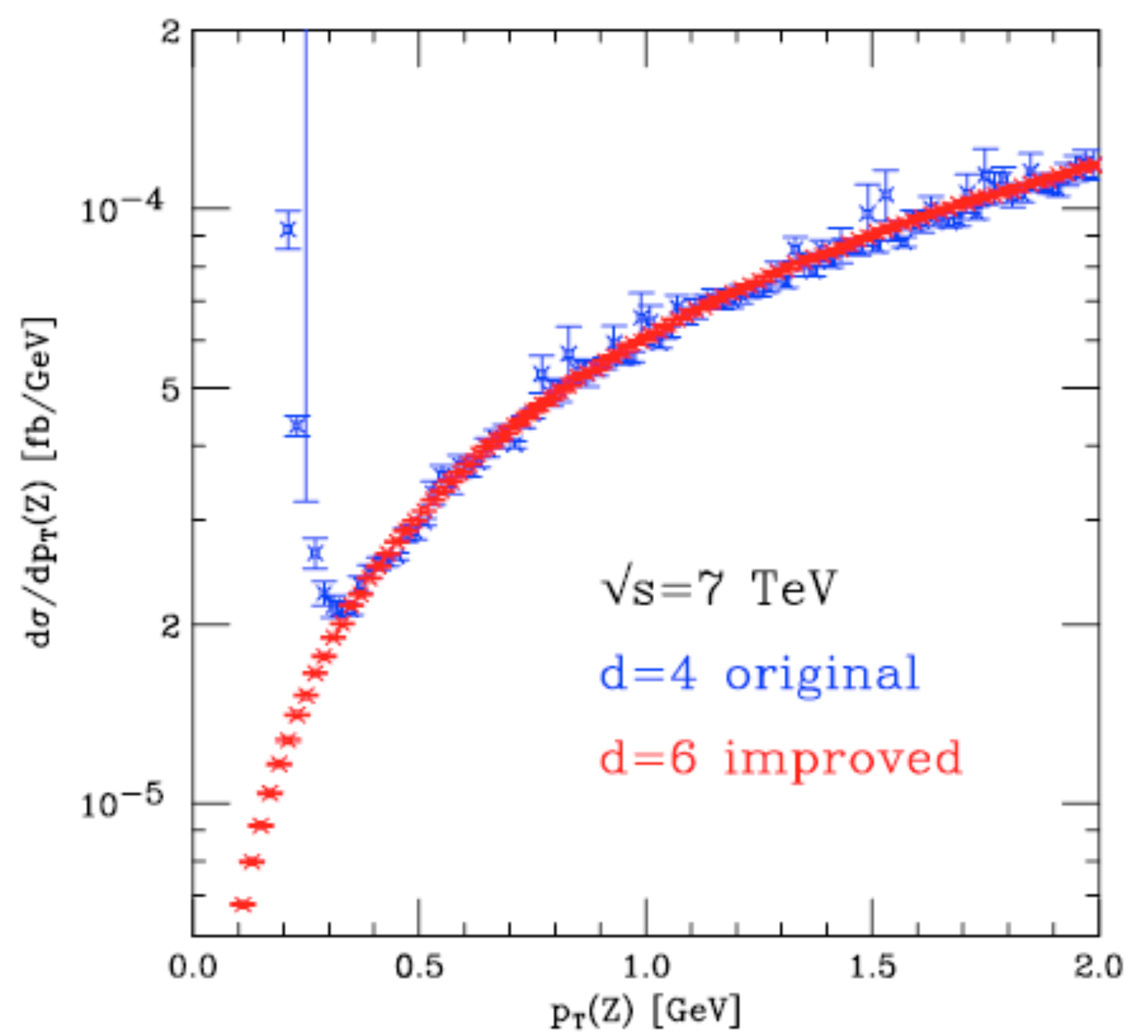
Campbell, Ellis, Williams, 1311.3589

$P_T=0$

- Translating back to Bjorken-Drell notation,

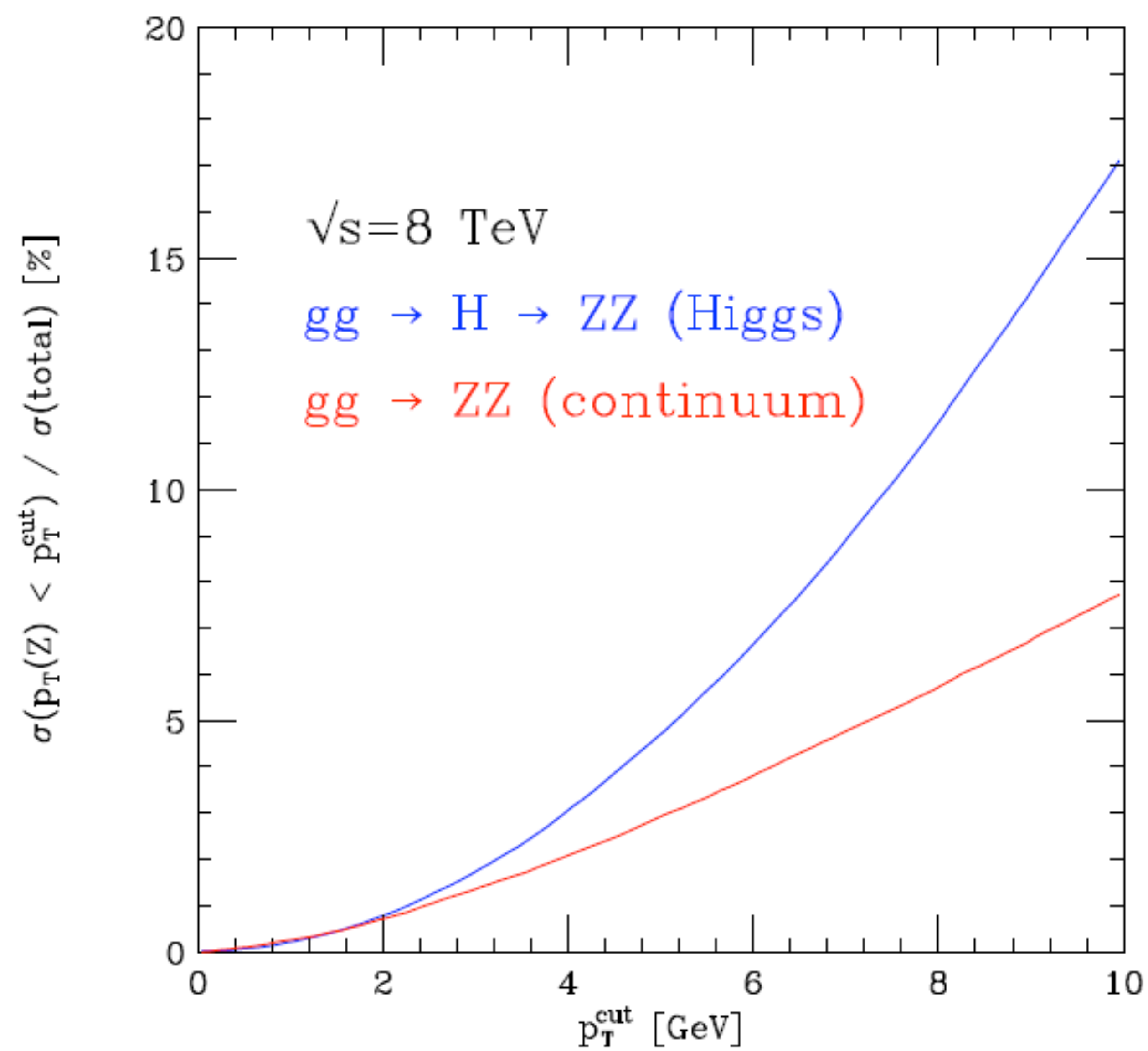
$$\langle 2|(3+4)|1] = \bar{u}_-(p_2)(\not{p}_3 + \not{p}_4)u_-(p_1)$$

- Singular when 3+4 is a linear combination of 1 and 2.
- Pernicious in this case, because we cut of p_T's of leptons, not $p_T(Z)=p_3+p_4$,
- The singularity is only apparent, but it can cause numerical problems.
- Clear numerical improvement when moving to new d=6 basis.



Why not just cut out the low p_T region?

- 8% of the $gg \rightarrow H \rightarrow ZZ^* \rightarrow e^- e^+ \mu^- \mu^+$ cross section, comes from the region where $p_T^Z < 7$GeV.
- We impose a cut of $p_T^Z < 0.1$GeV, (i.e. less than 0.01% of cross section.

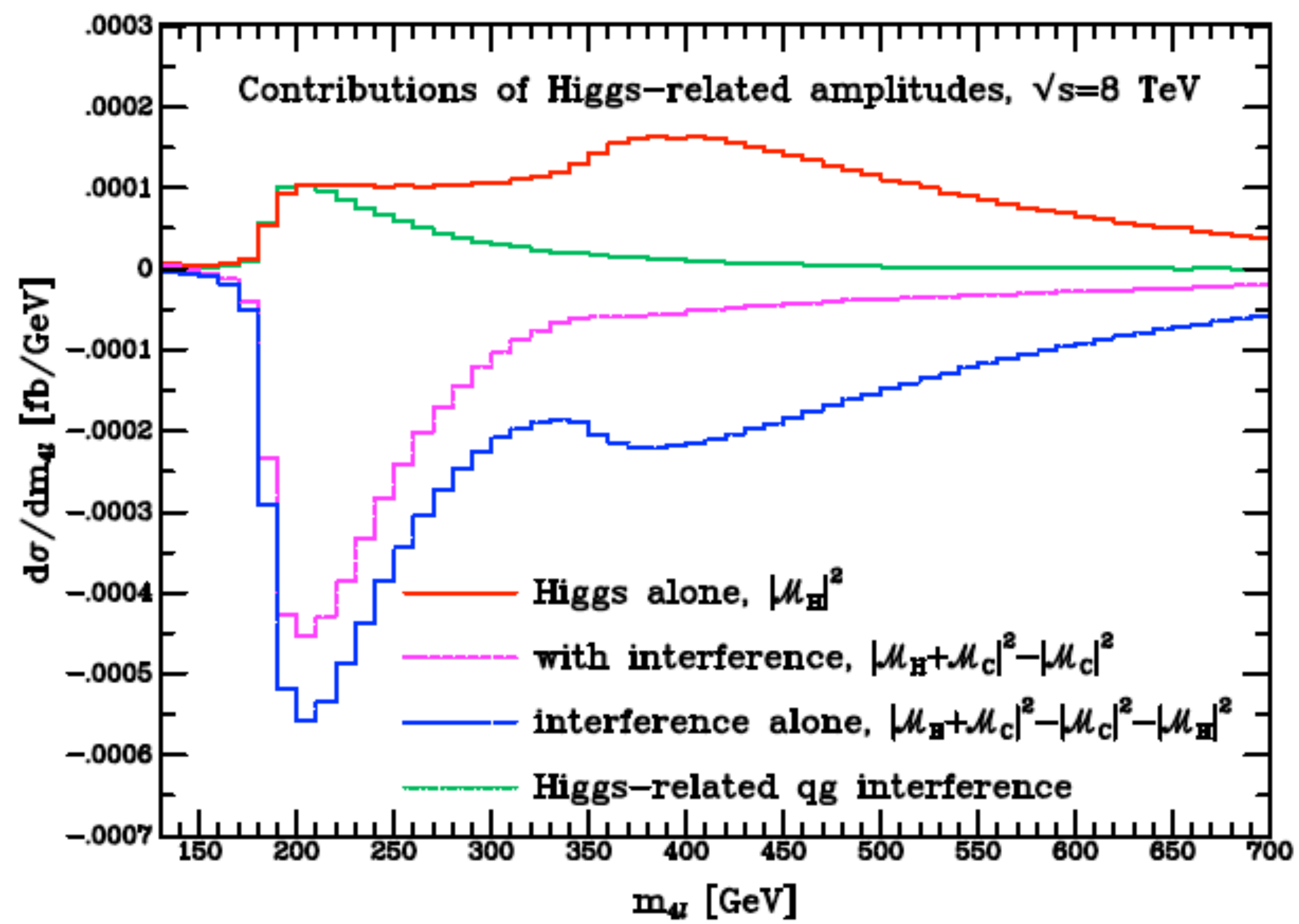


Size of interference @ 8 TeV

- Impossible to predict correct rate in the m_{4l}>200GeV region without correctly accounting for interference.

- For the SM Higgs boson, the interference is destructive and decreases the cross section.

- Higgs-related qg interference is not so big, especially above m_{4l}>300GeV



Rough and ready estimate of current bound on Γ_H

- Update of Caola-Melnikov analysis, using our best prediction.
- Using the results from our best prediction we find for $\sigma_{off} \equiv \sigma^H_{off} + \sigma^{int}_{off}$ at 8TeV.

$$\sigma_{off}(m_{4\ell} > 130\ \mathrm{GeV}) = 0.034\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.073\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$\sigma_{off}(m_{4\ell} > 300\ \mathrm{GeV}) = 0.025\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.036\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

- Therefore normalizing to the number of events observed at the peak we can estimate number of Higgs-related events off-peak (appropriately weighting to combine 7 and 8 TeV data).

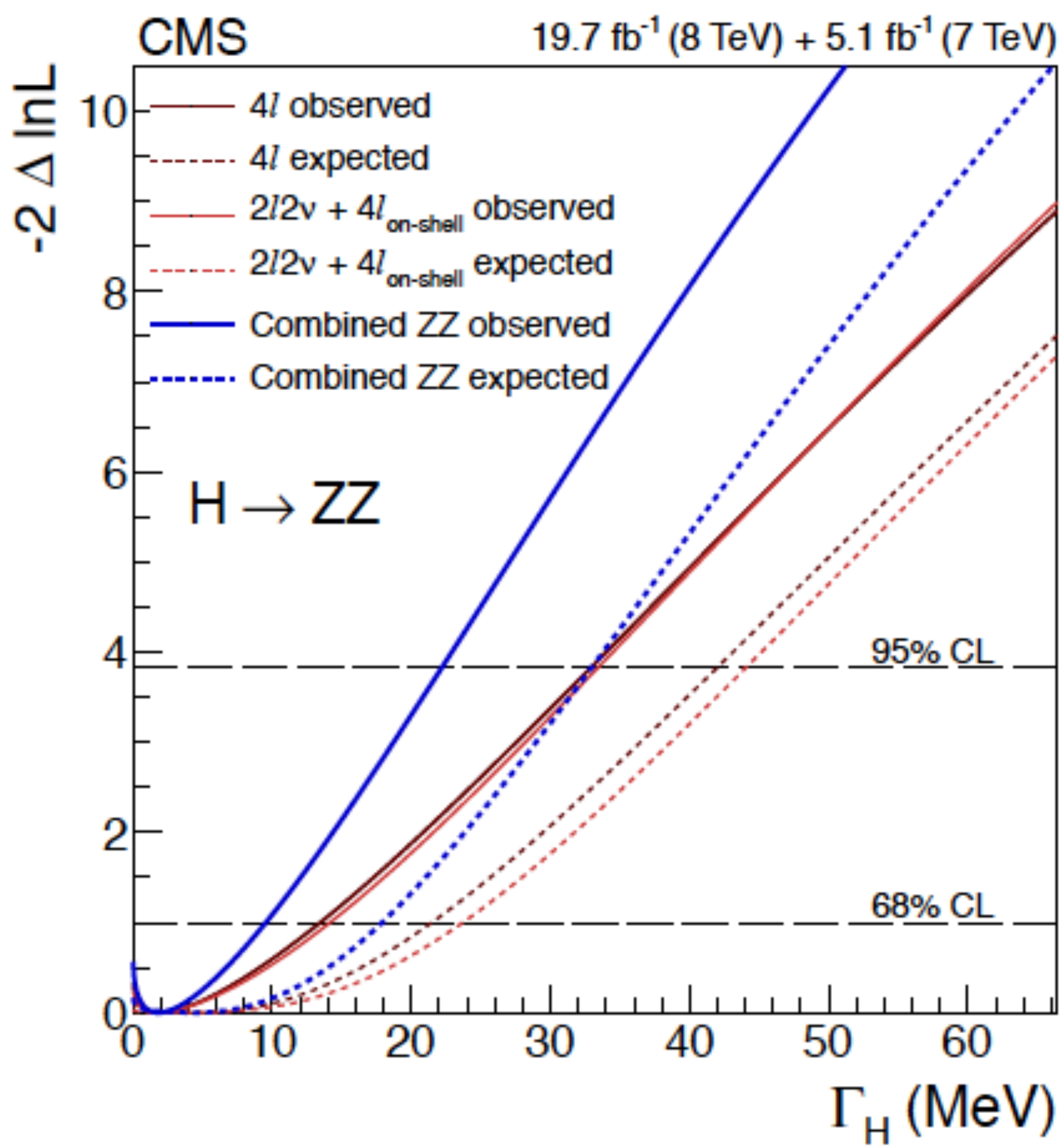
$$N^{4\ell}_{off}(m_{4\ell} > 130\ \mathrm{GeV}) = 2.78\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$N^{4\ell}_{off}(m_{4\ell} > 300\ \mathrm{GeV}) = 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

CMS result

arXiv:1405.3455

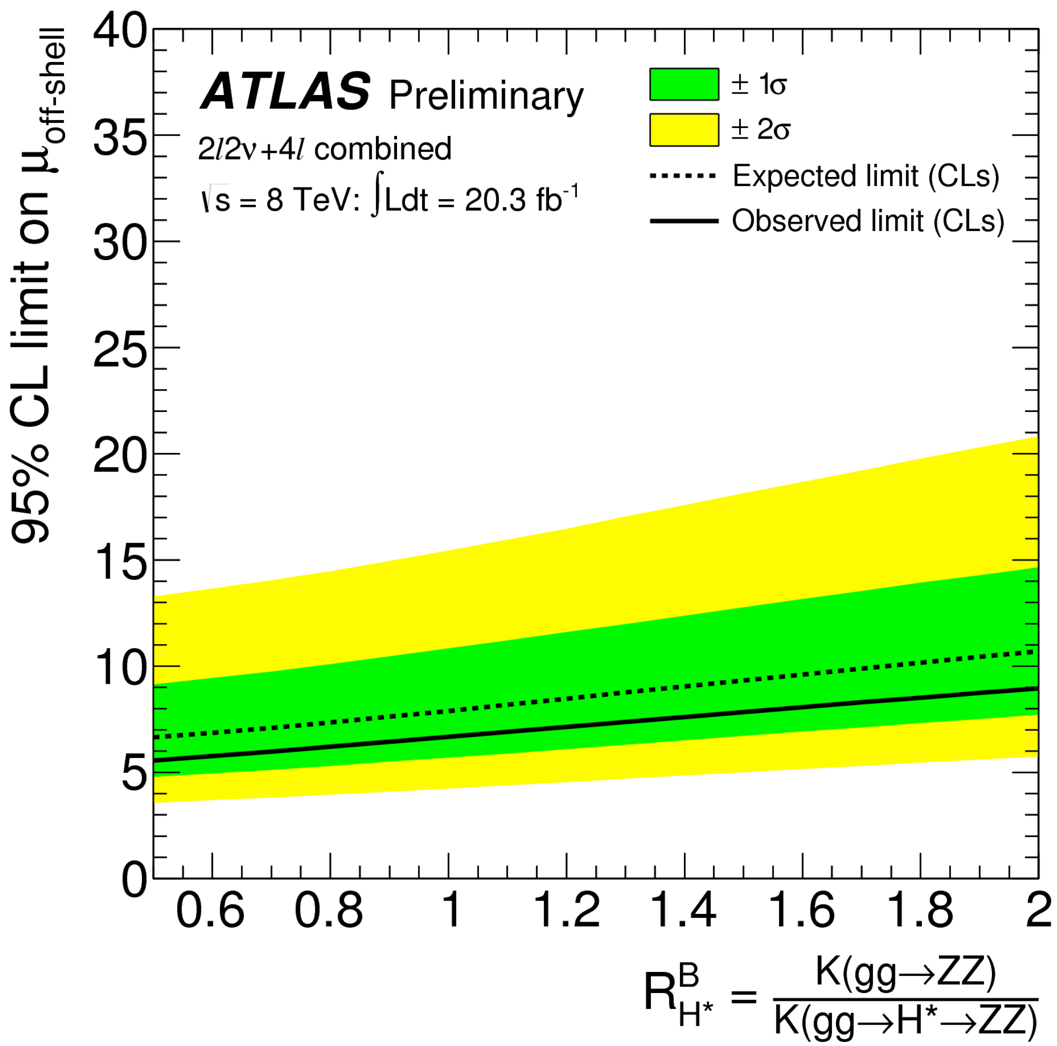
- Γ_H/Γ_H^{SM}=5.4 at 95%cl

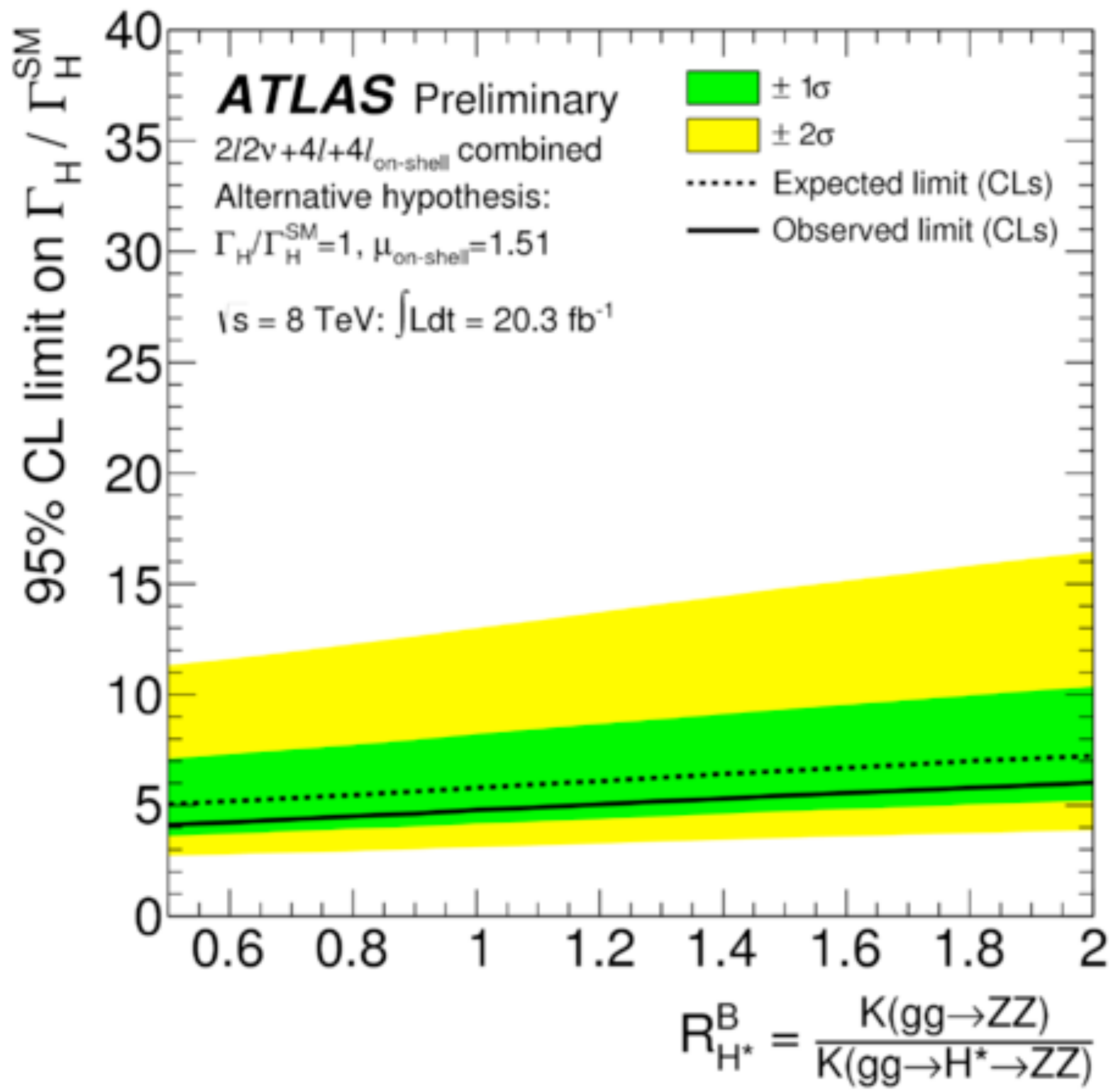


ATLAS result

ATLAS-CONF-2014-042

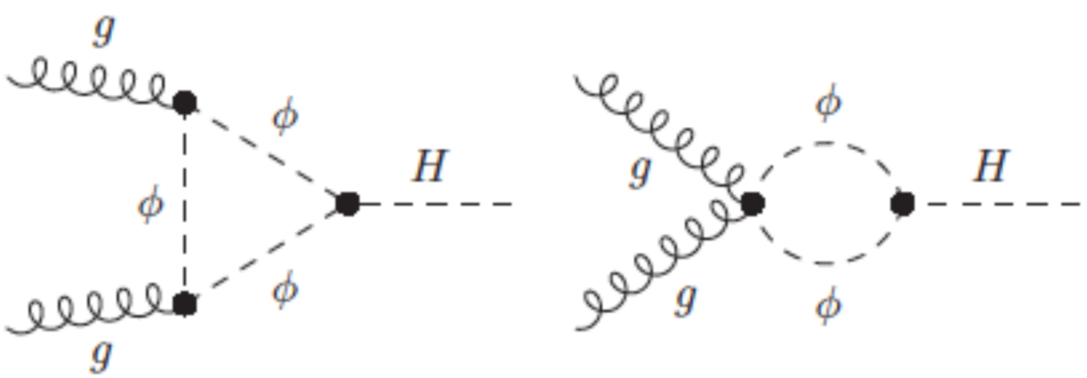
- Result for both off-shell coupling and width as a function of relative K-factor
- Γ_H/Γ_H^{SM}=4.8/7.7 at 95%cl





Model-dependence of Higgs width bound.

- It is possible to have models in which the unitarity relation between boxes and triangles is violated, e.g. introduction of a colored scalar of mass ~ 70GeV.



Englert and Spannowsky, 1405.0285

- This gives a potentially large contribution to gg→h which will have to be compensated to give μ=1 with corresponding changes in the width. Such scalar contributions are suppressed in the off-shell region.

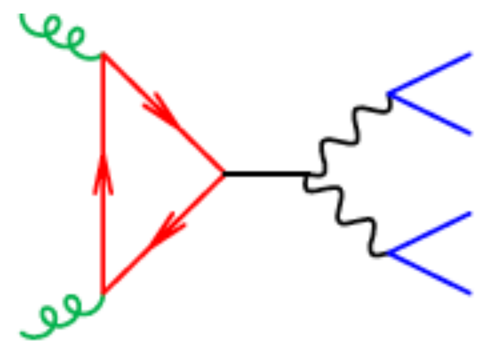
- In the future such models can be tested by looking at the on-shell/off-shell ratio in VBF production.

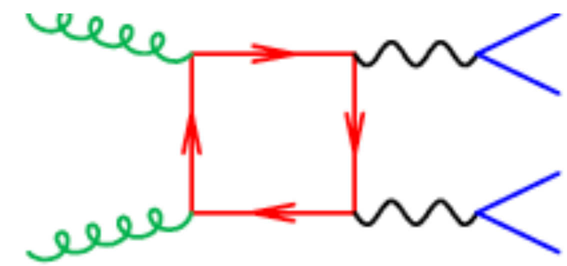
- Off-shell cross-section is useful to distinguish between Y_t and point-like couplings of the H.

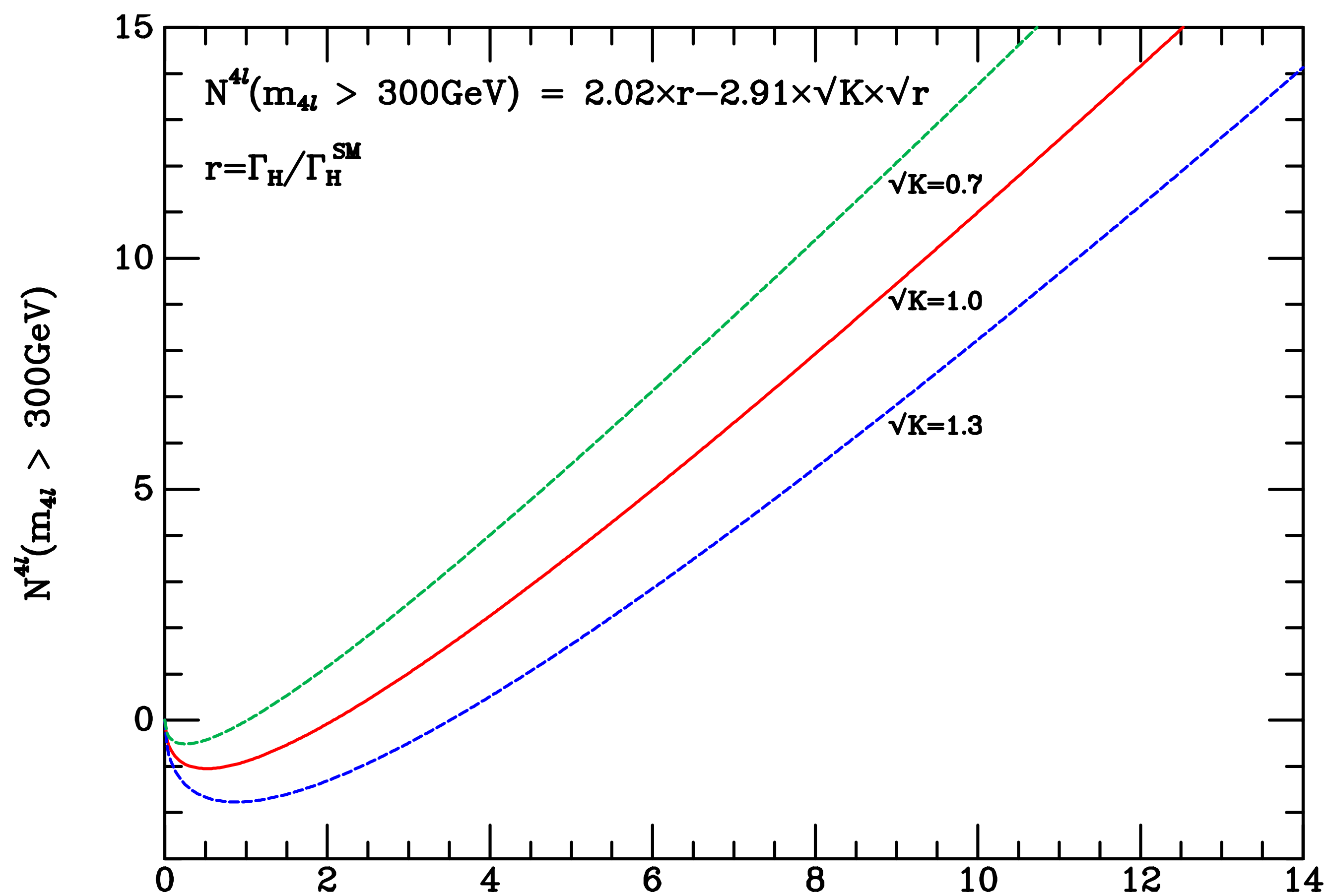
Cacciapaglia et al, 1406.1757
Azatov et al, 1406.6338

Impact of assumed K-factor on experimental limit

- As presented the calculation is LO, albeit at one loop.
- Higher order corrections to Higgs production are known, K-factor~2.2
- Higher corrections to continuum are not known. Curve shows impact of relative K factor.
- CMS assumes relative K factor=1±0.1





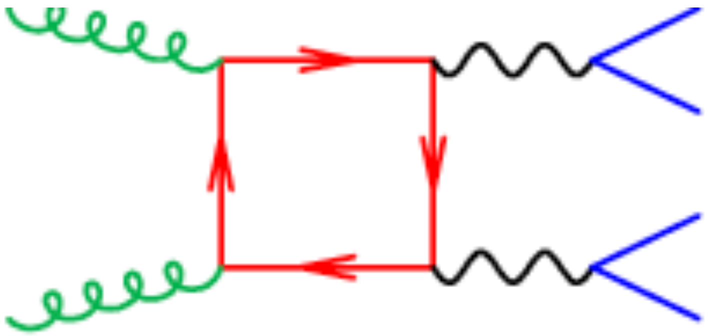


$$\frac{\Gamma_H}{\Gamma_H^{SM}} < \{3.0, 4.2, 5.75\} \text{ for } \sqrt{K} = \{0.7, 1.0, 1.3\}\,.$$

Rationale for assuming K=1?

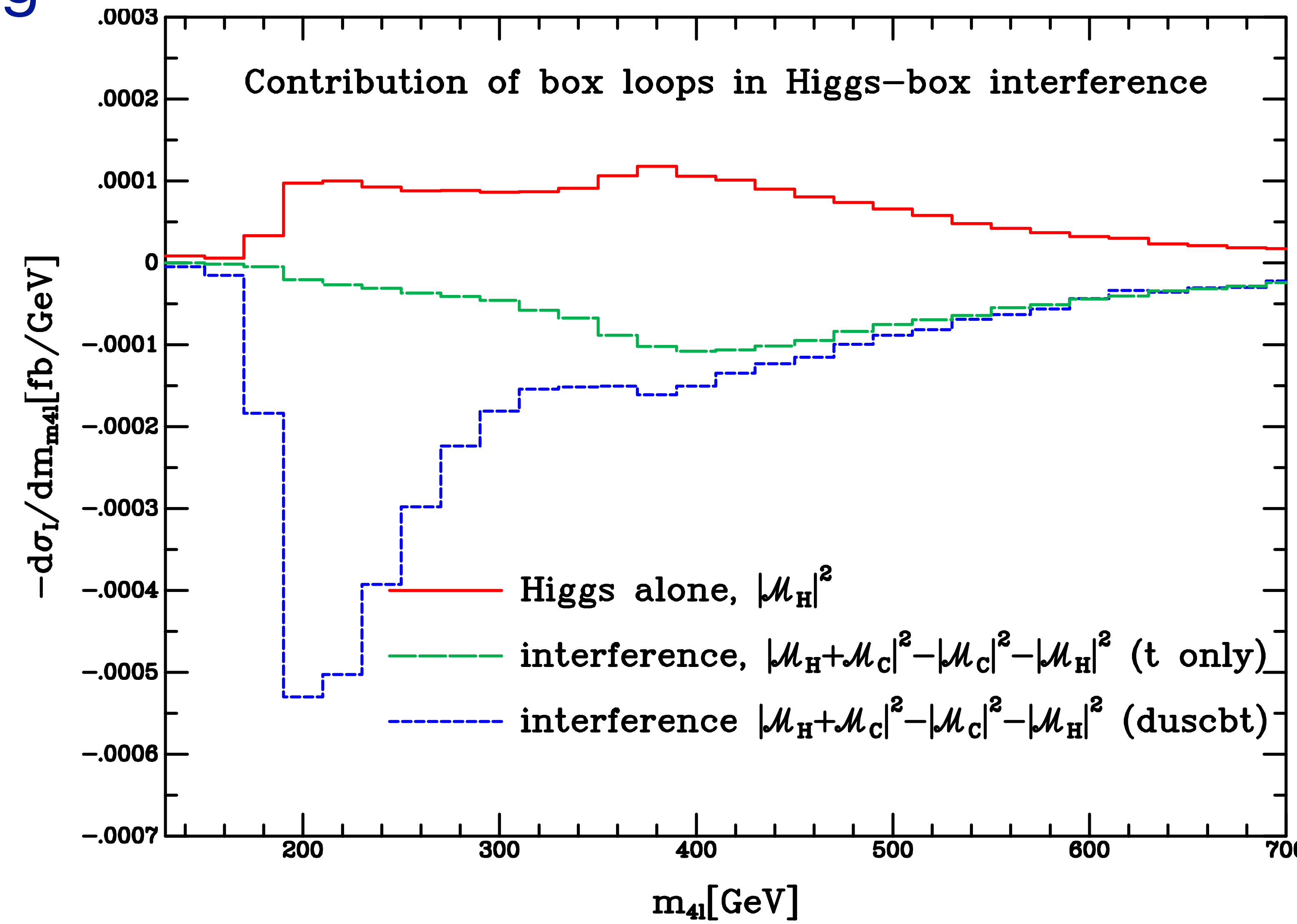
* K factor estimated in the soft gluon limit for H→WW and M_H=600GeV

  Bonvini et al, 1304.3053



* Coefficients estimated using the equivalence theorem and HH rate, for which higher order corrections have been calculated in heavy m_t limit.

  Dawson et al, hep/ph 9805244



* Longitudinal modes only dominate interference for m_{4l}>400GeV.

K=1 (continued)

* K factor estimated using soft ideas, applied to production of 600GeV Higgs boson $H \rightarrow WW$ (Bonvini et al, 1304.3053)

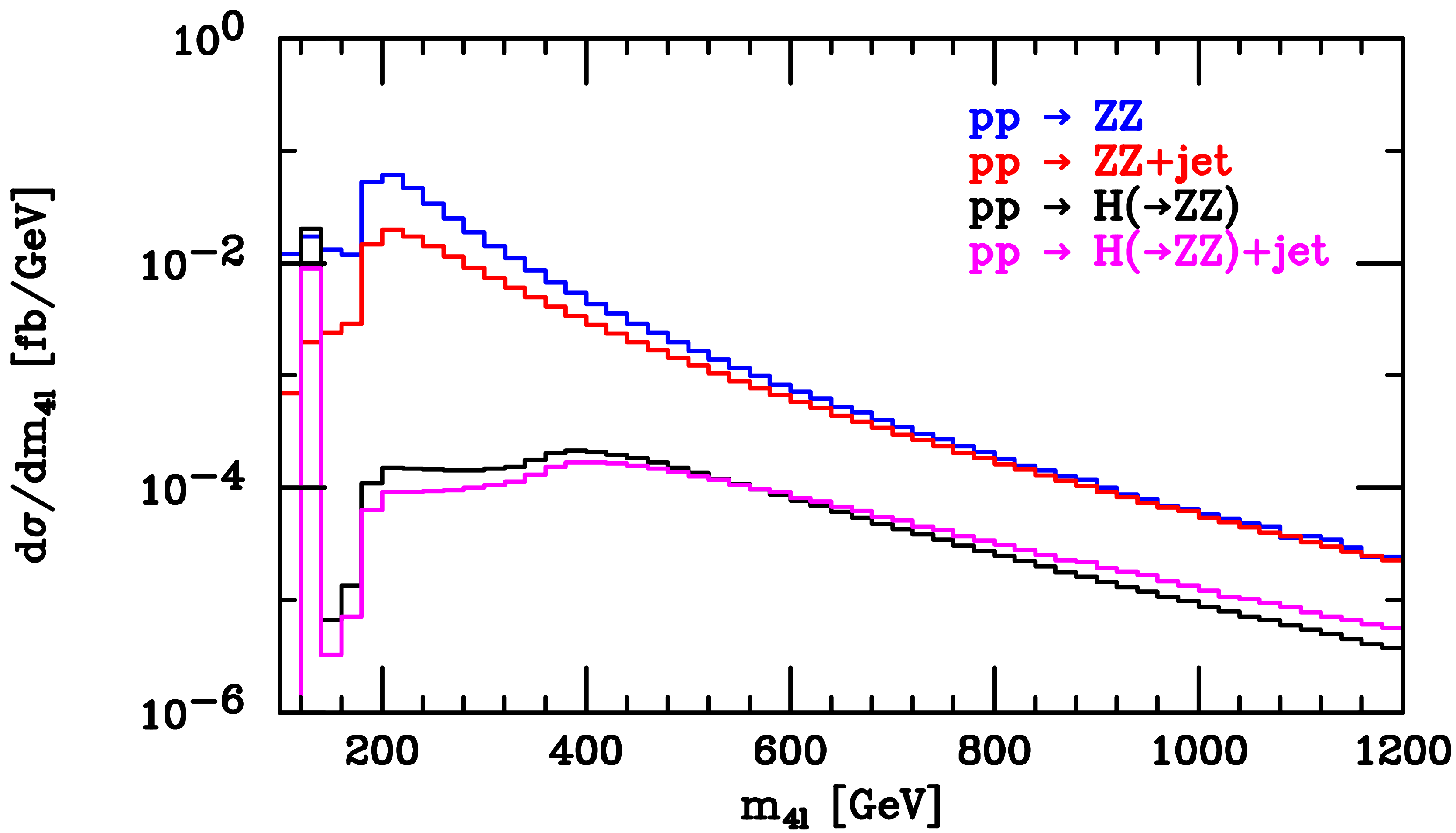
$$K \simeq 1 + \frac{\alpha_s}{2\pi}(2\pi^2 + c_1)$$

* c_1 is the process-dependent piece; central value taken from HH production, (assuming longitudinal modes dominate).
* Bonvini et al procedure, vary c_1 between $c_1/5$ and 5 c_1 to estimate uncertainty.
* Effect of this variation on K-factor shown to be ~6% for M_H=600GeV where the interference is a +15% effect
* Variation of c_1 can have a larger effect in our case, (perhaps ~30%) because interference is a -150% effect.
* We will only know for sure when we calculate the complete gg-initiated contributions at NLO, (Higgs portion is already known).

Interference in ZZ + jet.

Interference effects in ZZ+jet production

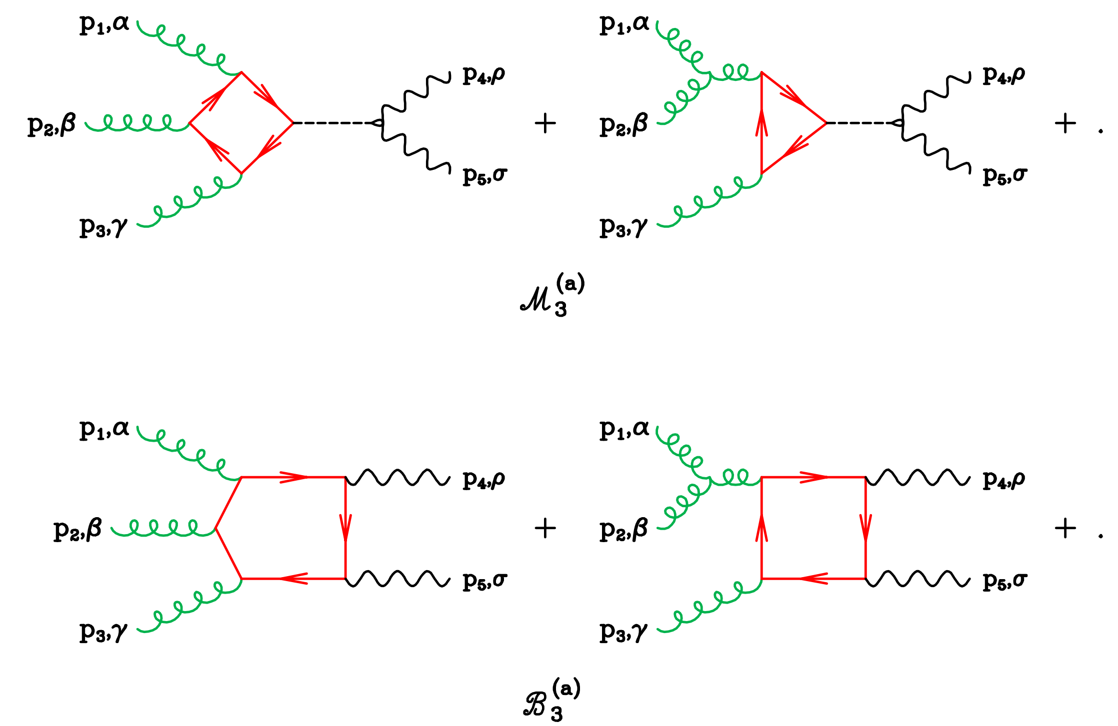
* Better signal to background ratio in the ZZ+jet channel.

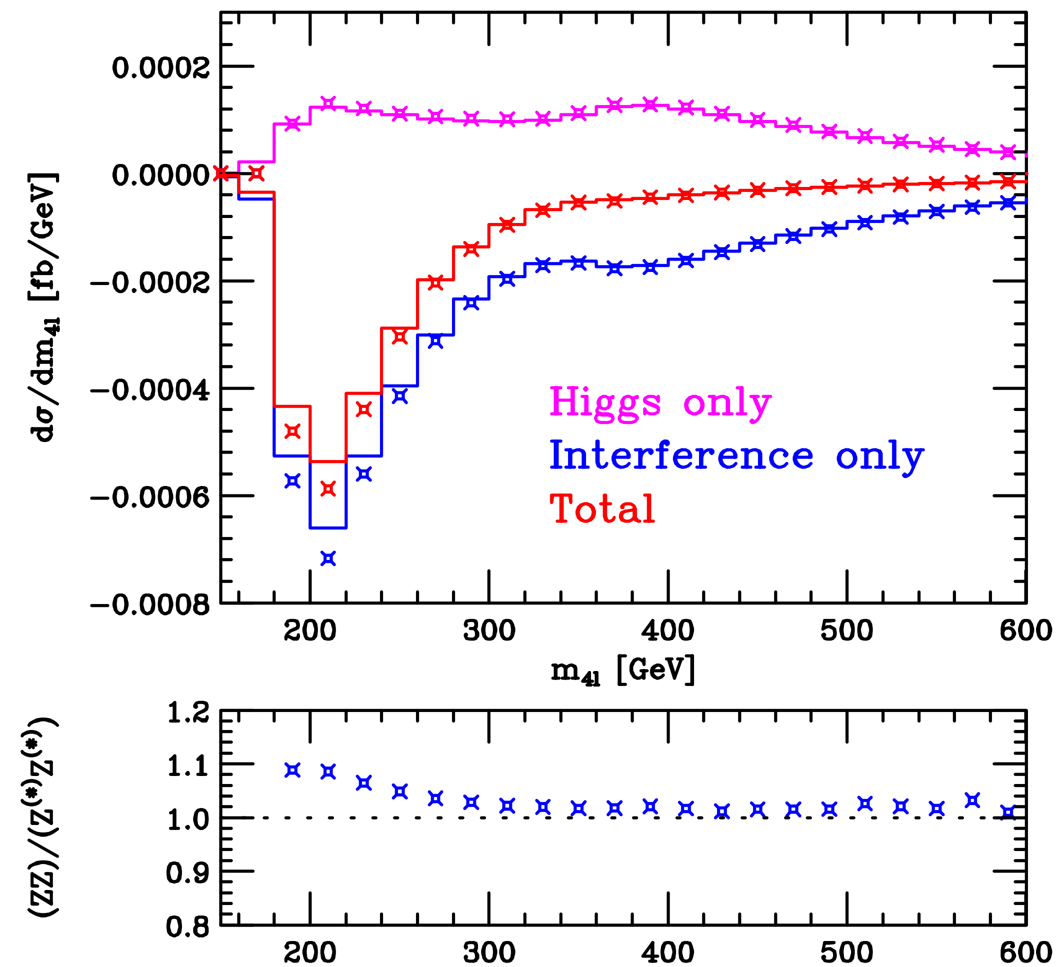


* For m_{4l}>300GeV,
  Higgs rate in 1-jet bin~ rate in 0-jet bin,
  whereas background rate is about 1.5 times smaller.

On shell approximation for ZZ+jet

- For simplicity, (in high mass region) treat Z-bosons as on-shell and sum over polarizations.
- Obtain analytic formula for interference.
- On-shell approximation is justified in the high mass region, (see figure).
- This is part of a NLO calculation of ZZ rate in high mass region.





Numerical results

* ZZ result with fiducial cuts on leptons:

$$\sigma^{H+I}_{off,4\ell-\text{fiducial}}(m_{4\ell} > 300\ \text{GeV}) = 0.025\left(\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}\right) - 0.036\sqrt{\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}}\ \text{fb},$$

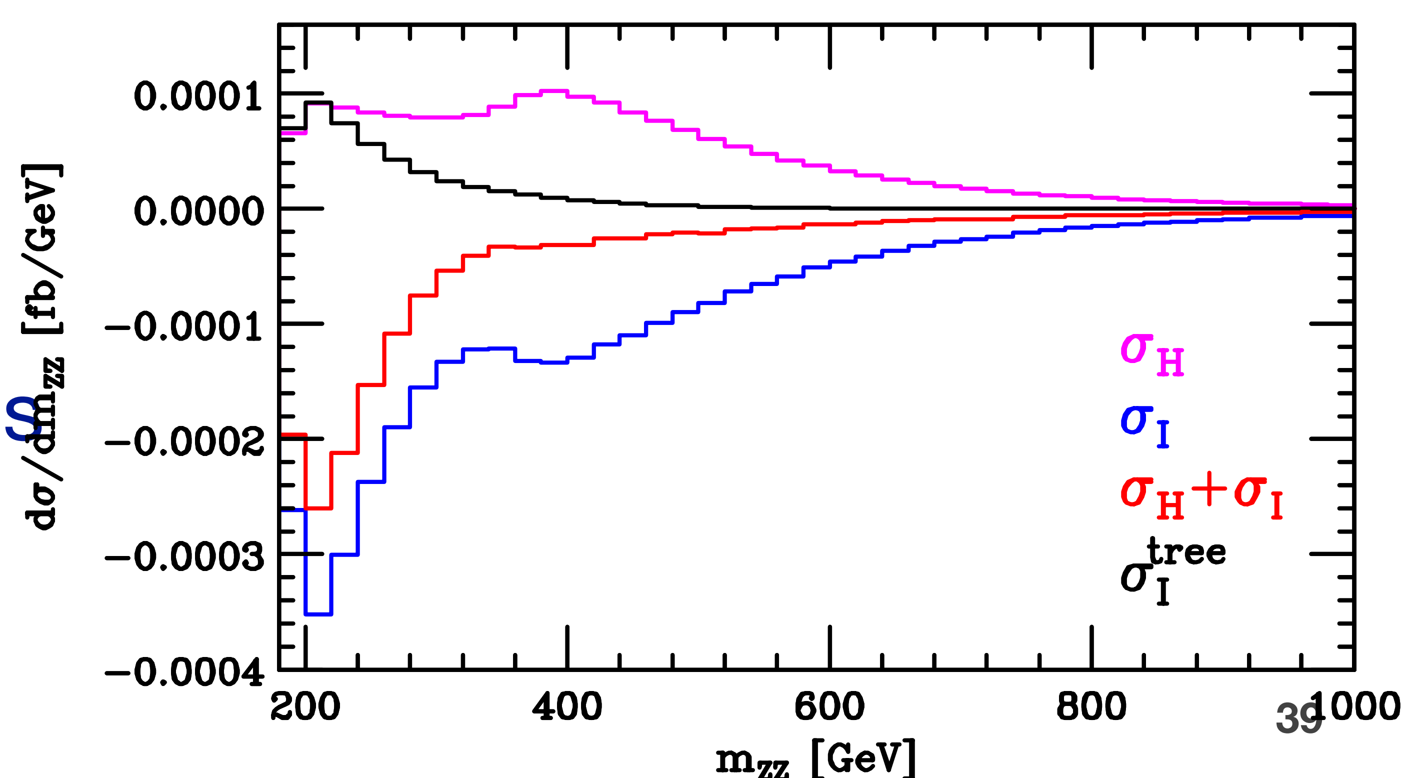
* ZZ result withouts fiducial cuts on leptons:

$$\sigma^{H+I}_{off,ZZ}(m_{ZZ} > 300\ \text{GeV}) = 0.0323\left(\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}\right) - 0.0468\sqrt{\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}}\ \text{fb}.$$

* ZZ+jet result (p_T(jet) > 30 GeV, no cuts on leptons)

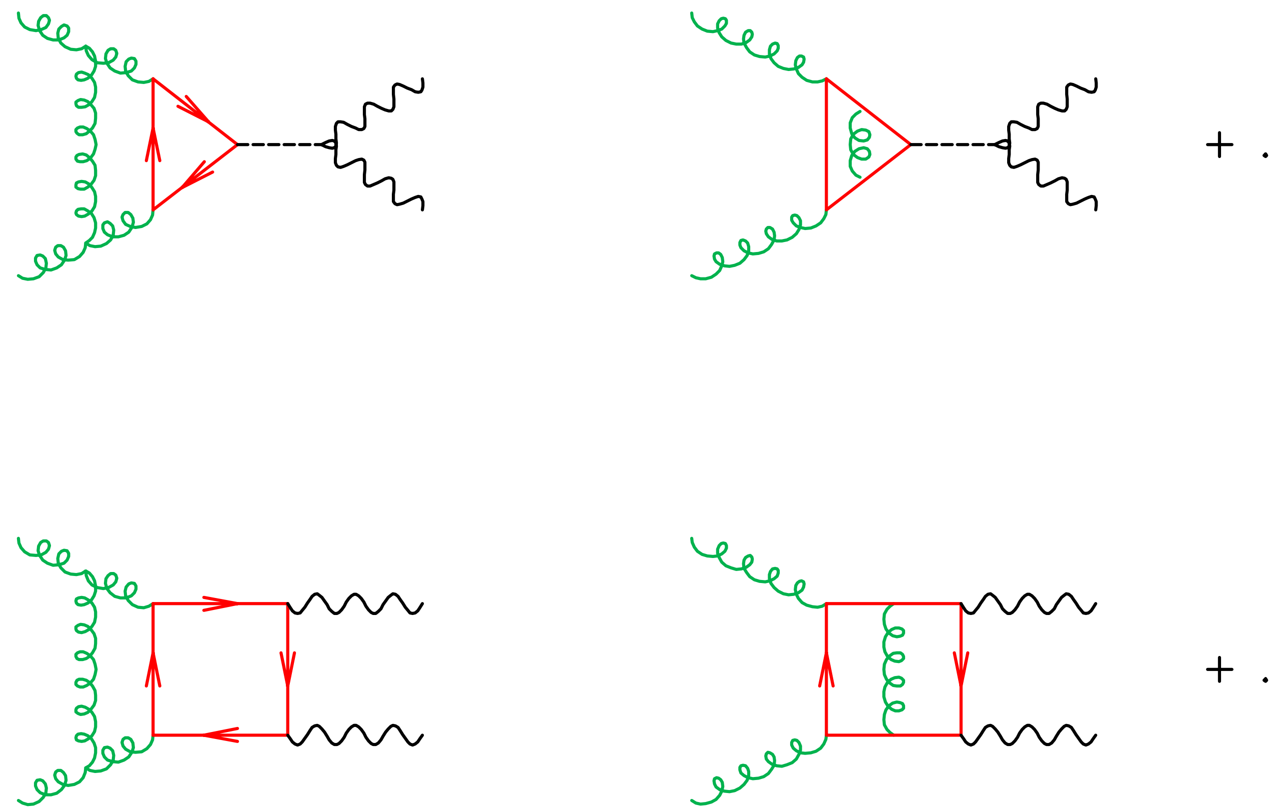
$$\sigma^{H+I}_{off,ZZ+jet}(m_{ZZ} > 300\ \text{GeV}) = 0.0280\left(\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}\right) - 0.0392\sqrt{\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}}}\ \text{fb},$$

* In the presence of the jet the pattern of interference is the same, but the total rate is smaller.In the presence of the jet the pattern of interference is the same, but the total rate is smaller.



Prospects for NLO calculation of ZZ rate

- ZZ+jet is the real emission computation.
- ZZ at two loops is the virtual calculation.
- Examples of two-loop diagrams
- Because of limited number of scales, s, t, M_Z, and m_t they should be amenable to calculation.



Summary

* With $3ab^{-1}$, mass shift in $\gamma\gamma$ will lead to an expected limit on width of $15\Gamma_{SM}$.
* MCFMv6.8 is a fast code for $gg \to ZZ \to 4l$ that is numerically stable because of analytic formulae (without recourse to multiple precision).
* Off-shell Higgs production in the 4-lepton channel will be an important tool in the determining Higgs properties.
* Measurements of off-shell couplings which when interpreted as limits on the width of the Higgs boson give stringent results.
* The current method is a based on a LO calculation with all the inherent uncertainties. The method shows sufficient promise that it merits a concerted effort to calculate NLO corrections to the $Z/\gamma^* Z/\gamma^* \to e^- e^+ \mu^- \mu^+$ process.
* ZZ+jet process gives important complementary information and should be pursued too. The pattern of interference in the 0-jet and 1-jet bins is similar.

Backup

Quantifying the interference-comparison with CM

- Our results for interference differ (slightly) from CM paper.
- We believe that the reason is that CM used the double precision version of the Kauer code gg2VV, that contains a cut at p_T<7GeV, for continuum related pieces.

Energy	σ^H_{peak}	$\sigma^H_{off}(m_{4l} > 130\text{ GeV})$	$\sigma^{int}_{off}(m_{4l} > 130\text{ GeV})$
7 TeV	0.203	0.044	-0.086
8 TeV	0.255	0.061	-0.118

Energy	σ^H_{peak}	$\sigma^H_{off}(m_{4l} > 300\text{ GeV})$	$\sigma^{int}_{off}(m_{4l} > 300\text{ GeV})$
7 TeV	0.203	0.034	-0.050
8 TeV	0.255	0.049	-0.071

Numbers @ 8 and 13 TeV.

$$\sigma^H : |\mathcal{M}_H|^2 , \quad \sigma^I : |\mathcal{M}_H + \mathcal{M}_C|^2 - |\mathcal{M}_C|^2 - |\mathcal{M}_H|^2$$

Cuts	$M_T < 130$ GeV		$M_T > 130$ GeV		$M_T > 300$ GeV	
	σ^H	σ^I	σ^H	σ^I	σ^H	σ^I
full	5.06	-0.0778	0.0262	-0.173	-	-
basic + $\Delta\phi_{\ell\ell}$	5.52	-0.0924	0.0844	-0.483	0.0021	-0.00888
basic	6.85	-0.117	0.328	-1.07	0.104	-0.240

Cuts	$M_T < 130$ GeV		$M_T > 130$ GeV		$M_T > 300$ GeV	
	σ^H	σ^I	σ^H	σ^I	σ^H	σ^I
full	11.3	-0.195	0.0658	-0.431	-	-0.000185
basic + $\Delta\phi_{\ell\ell}$	12.3	-0.233	0.222	-1.25	0.00698	-0.0283
basic	15.2	-0.296	1.04	-3.15	0.393	-0.893

- Interference is primarily an off-resonant phenomenon.
- Interference relatively more important than for ZZ
- With the basic cuts σ^{peak}(13TeV)≈ 2 σ^{peak}(8TeV) whereas $\sigma^{\text{off-peak}}$(13TeV)≈ 3 $\sigma^{\text{off-peak}}$(8TeV), so method will improve with energy.

MCFM 6.8 (26-April-2014)

New

- Extension of treatment of 4 lepton final states in WW and ZZ production, including Higgs-mediated processes (gg)
- Treatment includes both qq,qg,(α_s) and gg(α_s^2)
  - Addition of identical particles $ZZ \to e^- e^+ e^- e^+, \to \mu^- \mu^+ \mu^- \mu^+$
  - Addition of interference $ZZ \to e^- e^+ \nu_e \nu_e, W^- W^+ \to e^- \nu_e e^+ \nu_e$
  - Added new processes to streamline the calculation of components of the $W^- W^+$ processes.
- New diphoton+jets and triphoton processes.
- Les Houches events for select leading order processes.

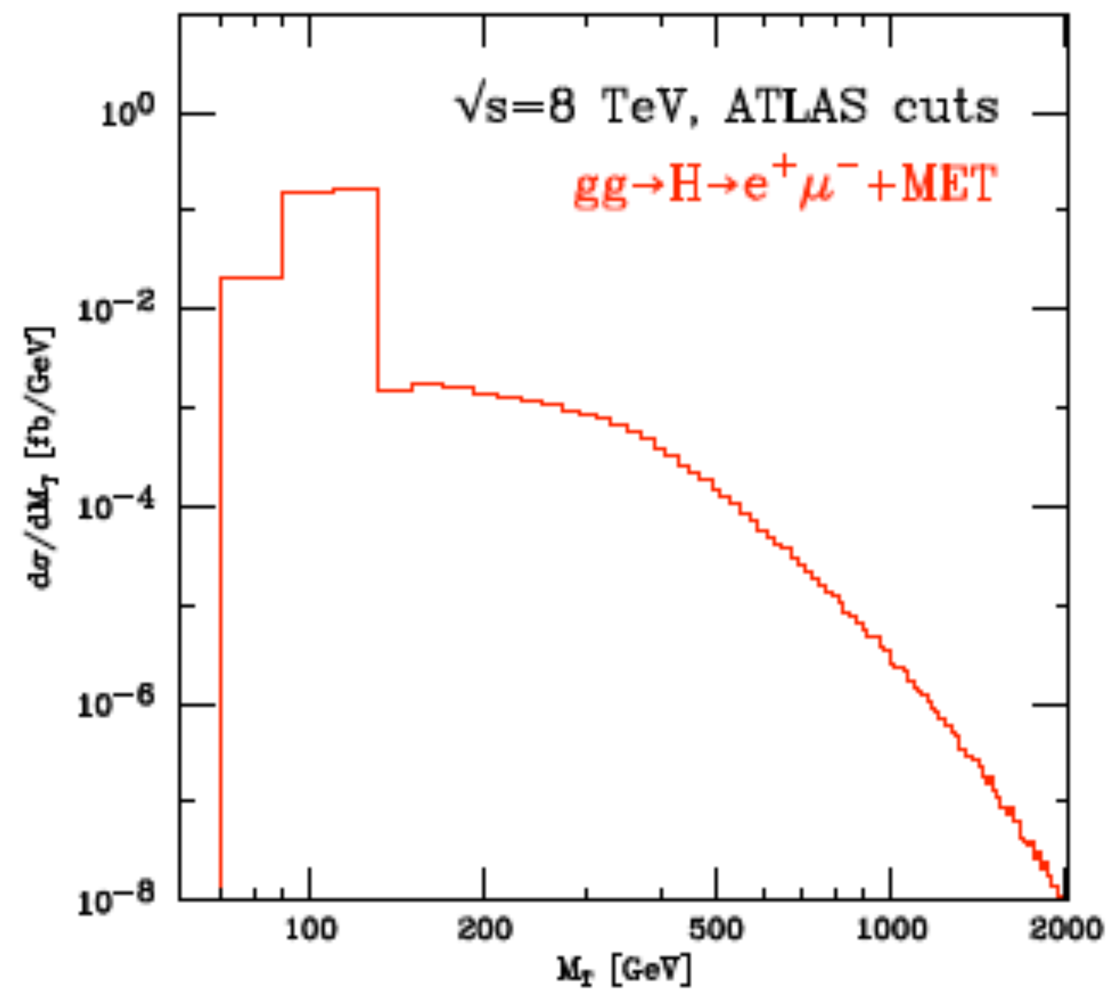
WW

Campbell, Ellis, Williams,1312.1628

* The ZZ channel is convenient: well measured leptons allow the Higgs boson line shape to be mapped out and peak/off-peak regions to be directly identified.
* However the line shape is not crucial, just need well-separated regions, corresponding to on- and off-resonance.
* Play the same game for the WW channel $gg \to W^+W^- \to e^+\mu^-\nu_e\nu_\mu$
* As a proxy for the invariant mass, use the transverse mass of the expected WW system.

$$M_T^2 = (E_T^{miss} + E_T^{\ell\ell})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2$$

* Some features are washed out, but clear separation between peak and tail remains.



WW vs ZZ

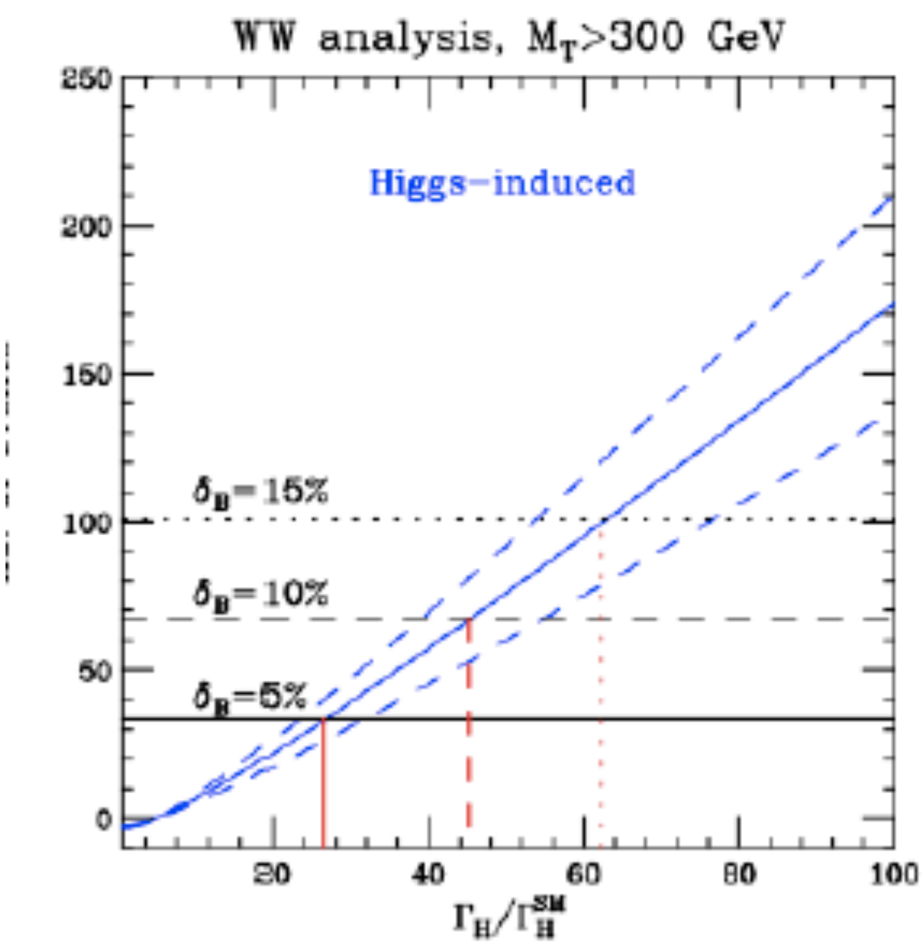
- Advantages
  - Threshold for two real W's much closer than for Z's
  - branching ratio to leptons higher
  - combined, two orders of magnitude more events

$$\mathrm{Br}(H \to WW) \times \mathrm{Br}(W \to \ell\nu)^2 = 2.7 \times 10^{-3}$$
$$\mathrm{Br}(H \to ZZ) \times \mathrm{Br}(Z \to \ell^+\ell^-)^2 = 3.2 \times 10^{-5}$$

- Disadvantages
  - Much less clean, so more backgrounds,
  - Even observation of the Higgs boson in this channel not yet confirmed.
  - Top-related background that require a jet veto
  - Summing large logarithms in jet-veto cross section changes large m_{4l} behavior, in such a way that potential limits are degraded by about a factor of 2. Moult-Stewart 1405.5534

Estimate of sensitivity

- Cuts to isolate Higgs peak signal remove tail, so some cuts must be lifted.
- Requires more of a leap of faith than ZZ estimates, since ATLAS uncertainties only presented in the resonance region.
- Extrapolation, estimation of backgrounds, systematic uncertainties.



- <B>=336 events
- Try to be conservative by using systematic uncertainty on theory and choice of experimental systematics.

$$\boxed{\Gamma_H < 45^{+9}_{-7}\,\Gamma_H^{\mathrm{SM}}}$$

- Different flavor eμ, 20fb^{-1}, δ_B=10%