

Multi-Boson Production and Higgs Width Measurements

BNL, October 30, 2014

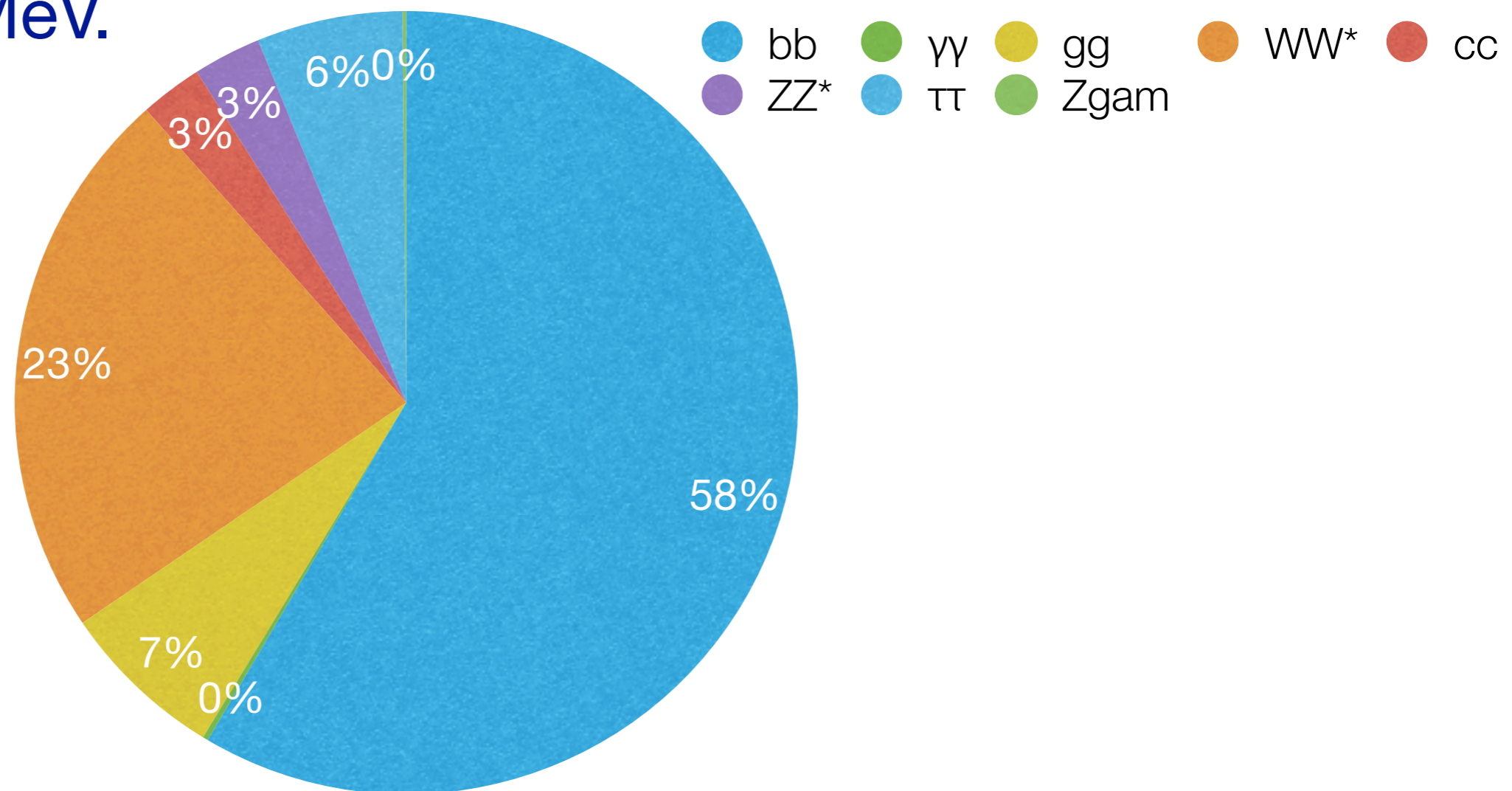
Keith Ellis, Fermilab

-
- * $ZZ^{(*)} \rightarrow 4$ 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 $\gamma\gamma, ZZ^*$.
- * ZZ^* is 3%, before BR to observable mode.
- * $\Gamma_H^{\text{SM}} \approx 4 \text{ MeV}$.



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 $\Gamma_H < 1600 \Gamma_H^{\text{SM}}$

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}	$\sim 1.5 \times 10^{-12}$

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

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

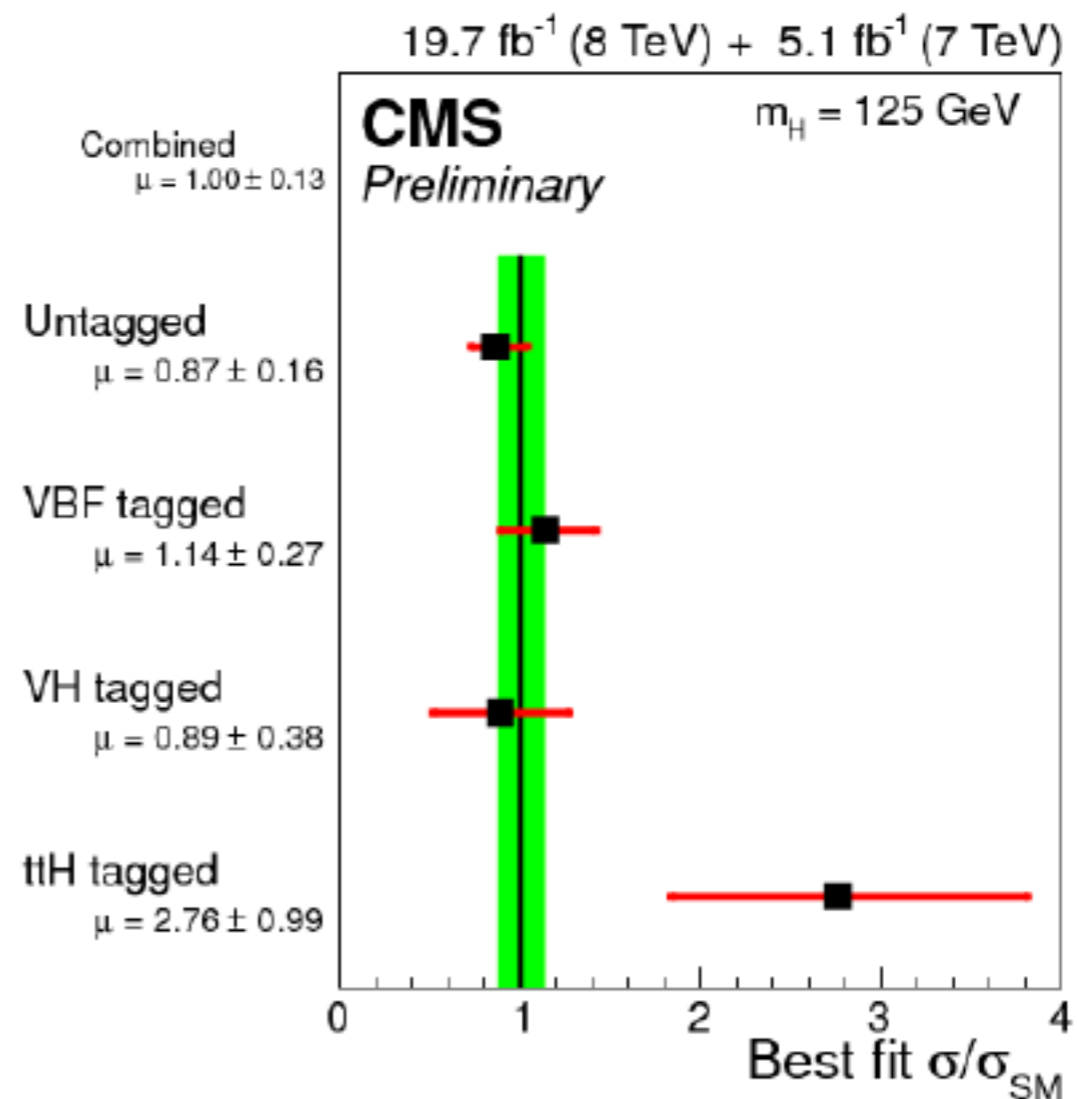
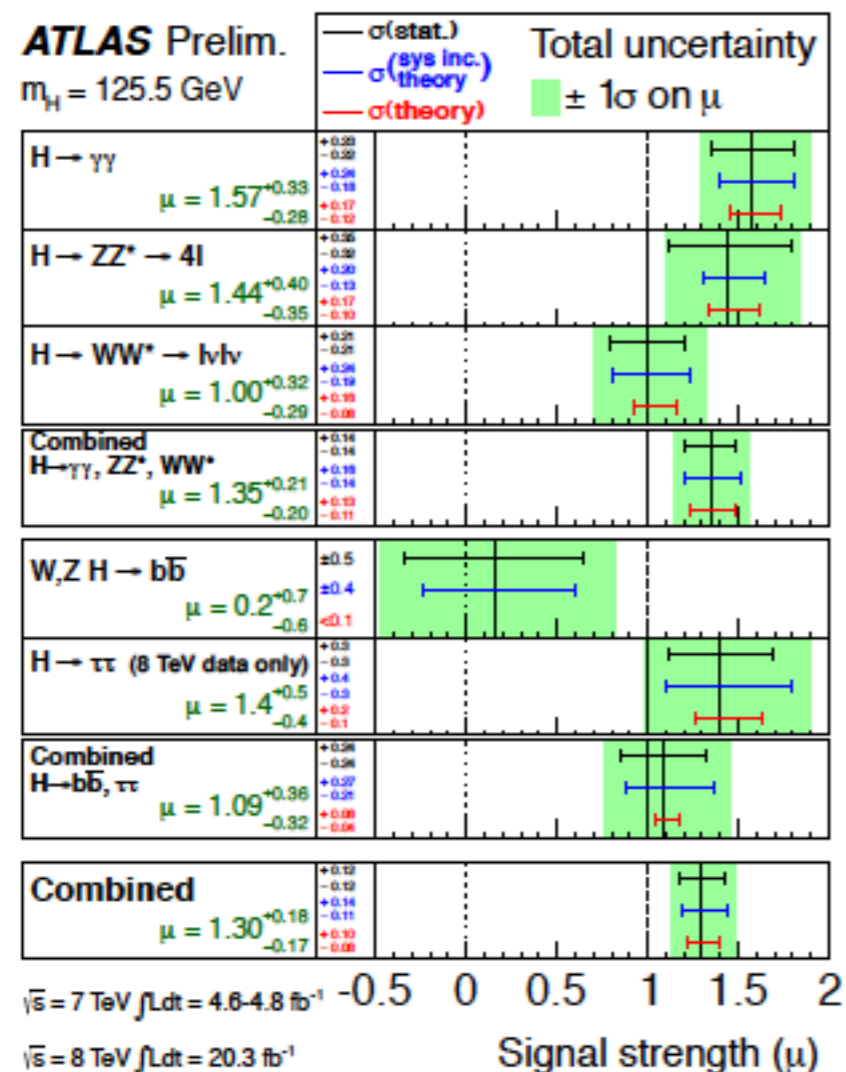
- * Measurements on the Higgs peak, are only sensitive to the ratio, $\frac{g_i^2 g_f^2}{\Gamma_h}$

- * Performing the rescaling by ξ leaves the measurement unchanged.

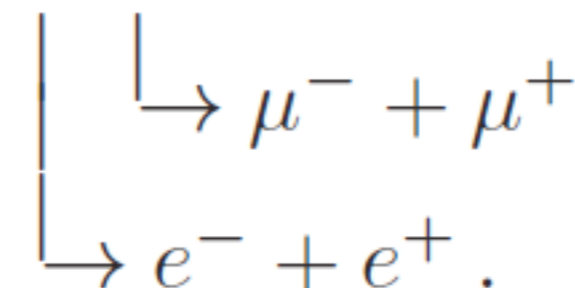
$$\begin{aligned} g_i &\rightarrow \xi g_i \\ g_f &\rightarrow \xi g_f \\ \Gamma_H &\rightarrow \xi^4 \Gamma_H \end{aligned}$$

Signal strength measurements

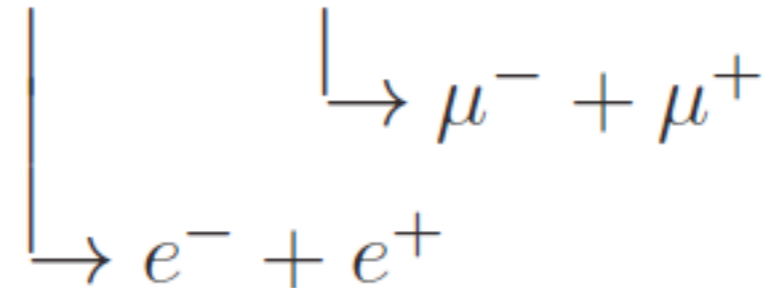
- * Signal strength measurements, (that assume a value for the total width), confirm that $g_i^2 g_f^2 / \Gamma_h$ is close to its standard model value (with ~20% errors)



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

$$p + p \rightarrow H \rightarrow ZZ$$


The diagram shows a central vertical line representing the Higgs boson. From the top of this line, a horizontal line extends to the right, labeled $\mu^- + \mu^+$. From the bottom of the central vertical line, a horizontal line extends to the right, labeled $e^- + e^+$.

$$p + p \rightarrow Z/\gamma^* + Z/\gamma^*$$


The diagram shows a central vertical line representing the initial state. From the top of this line, a horizontal line extends to the right, labeled $\mu^- + \mu^+$. From the bottom of the central vertical line, a horizontal line extends to the right, labeled $e^- + e^+$.

* Consider the contributing Feynman diagrams.

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

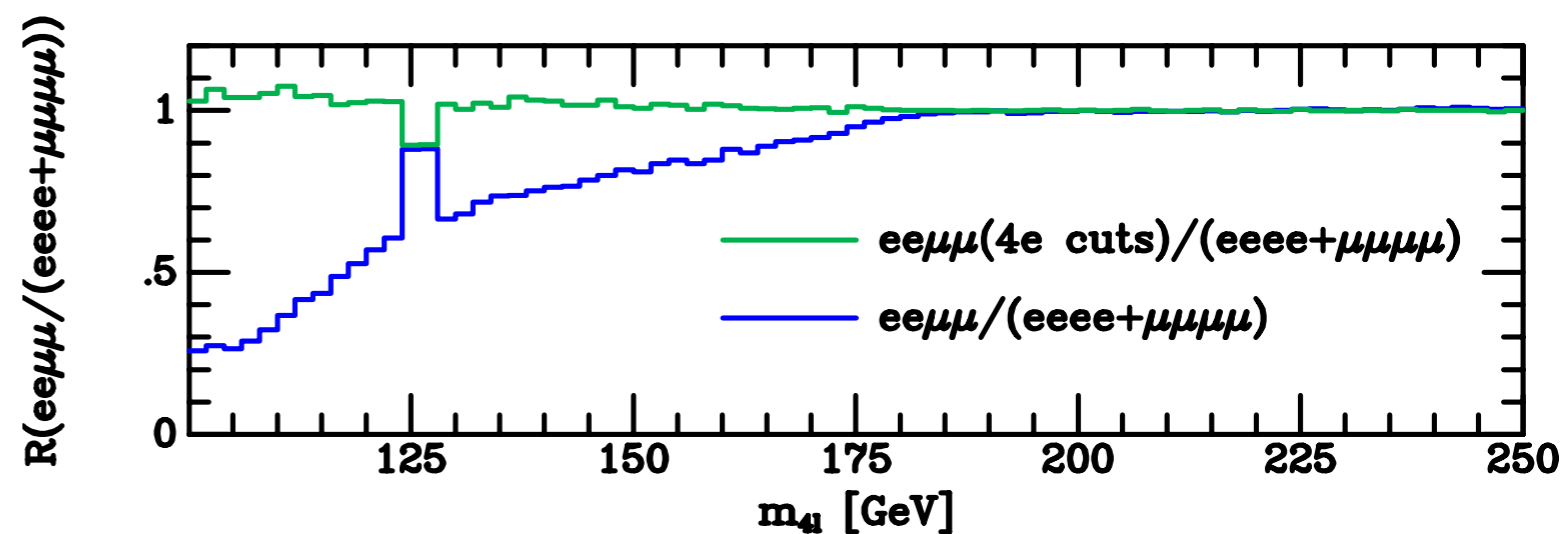
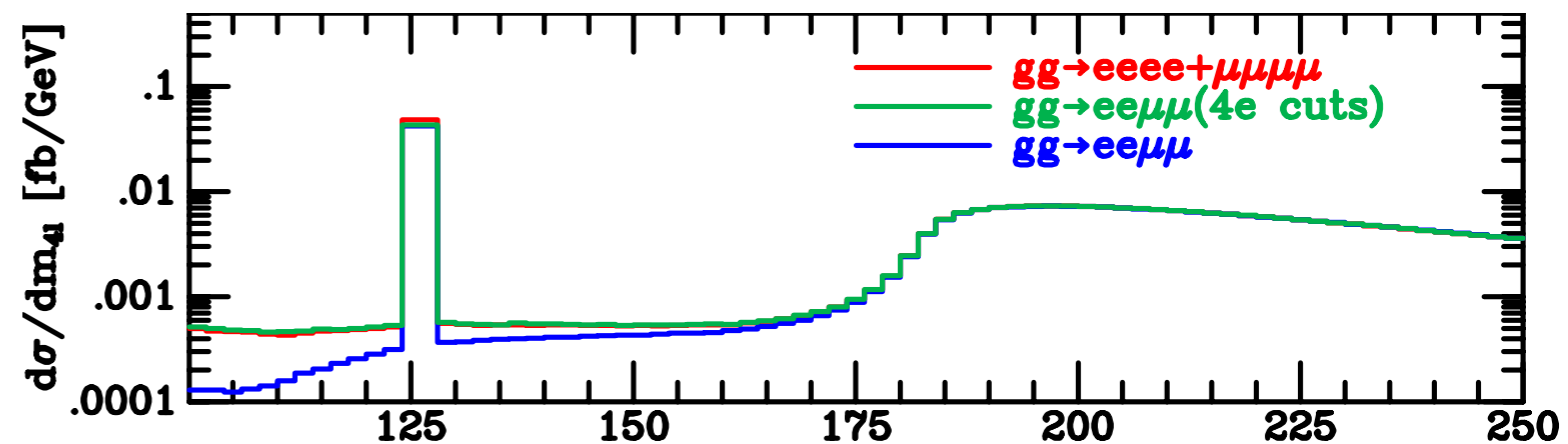
Identical particle effects in gg processes

* 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⁺μ⁻μ⁺ in the standard model

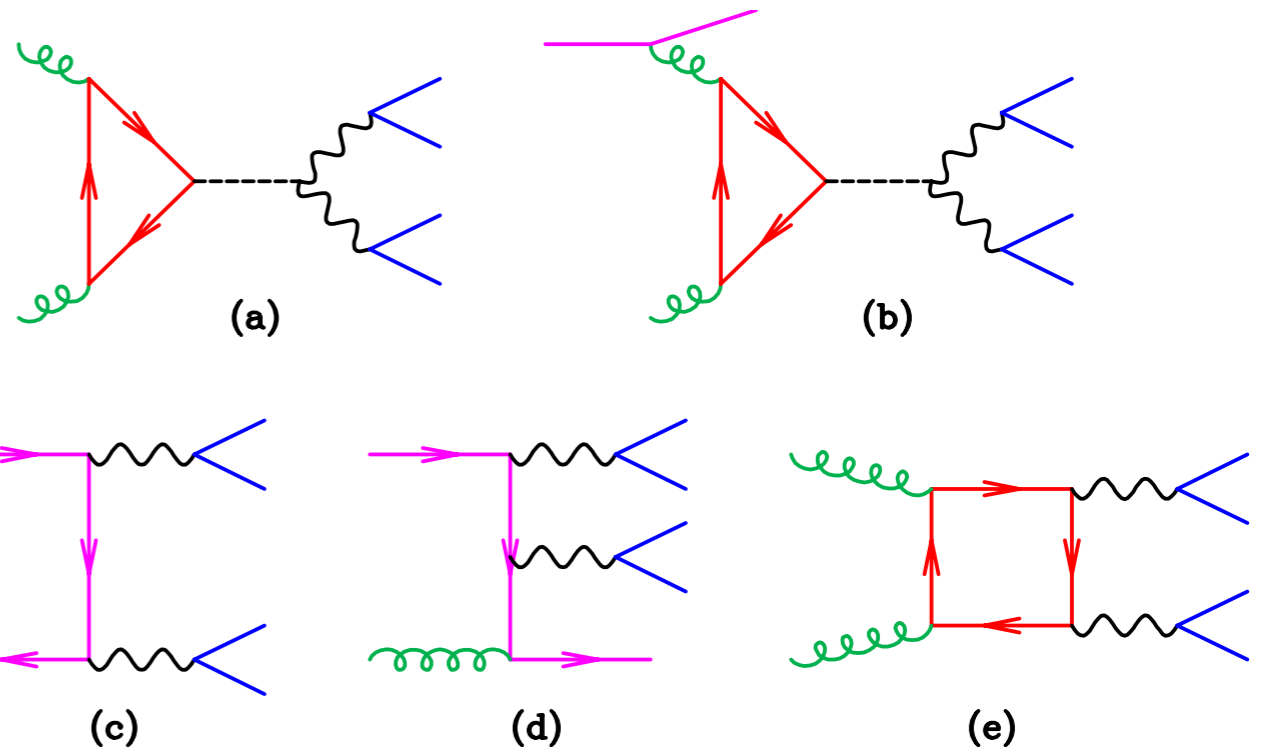
* Mishmash of orders in perturbation theory

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

* 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?

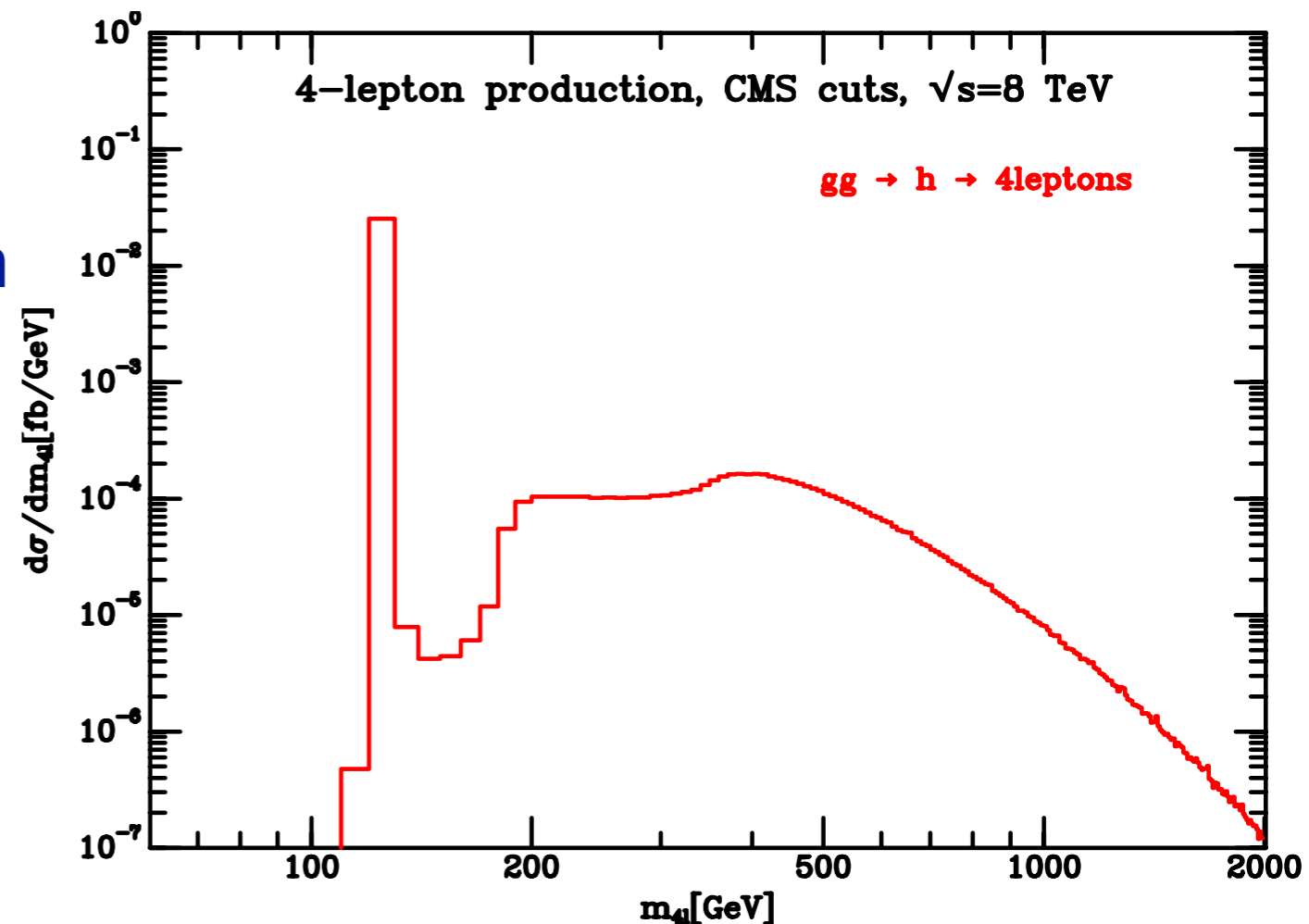
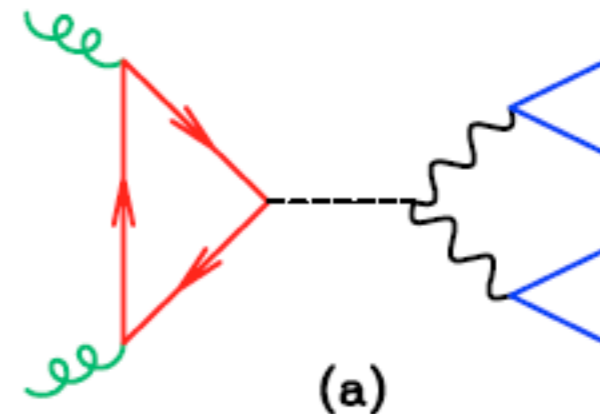
* $\Gamma_H / M_H = 1/30,000$

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

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

Kauer, Passarino, arXiv:1206.4803

* Similar tail for $H \rightarrow WW$.

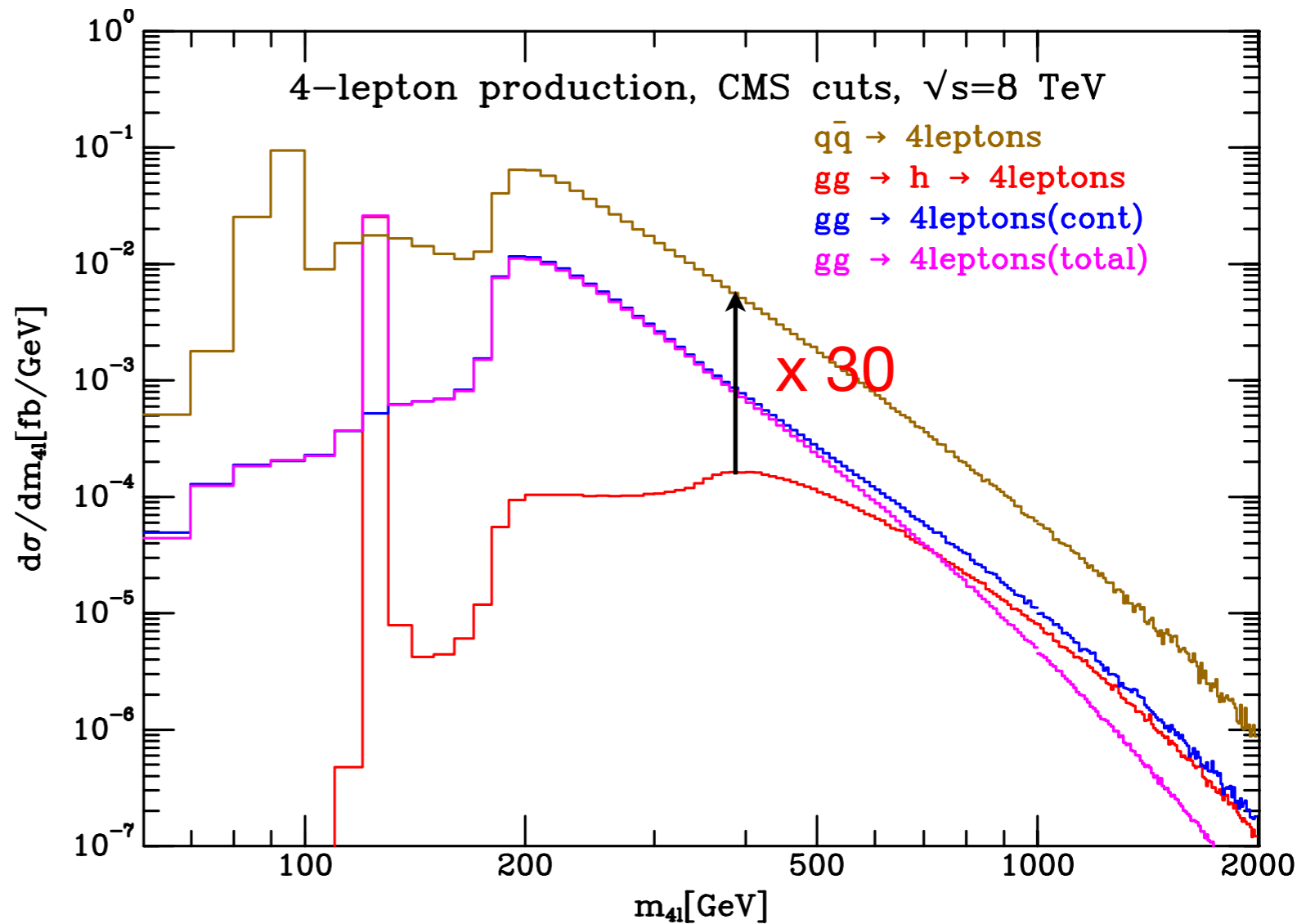


The big picture @ 8TeV

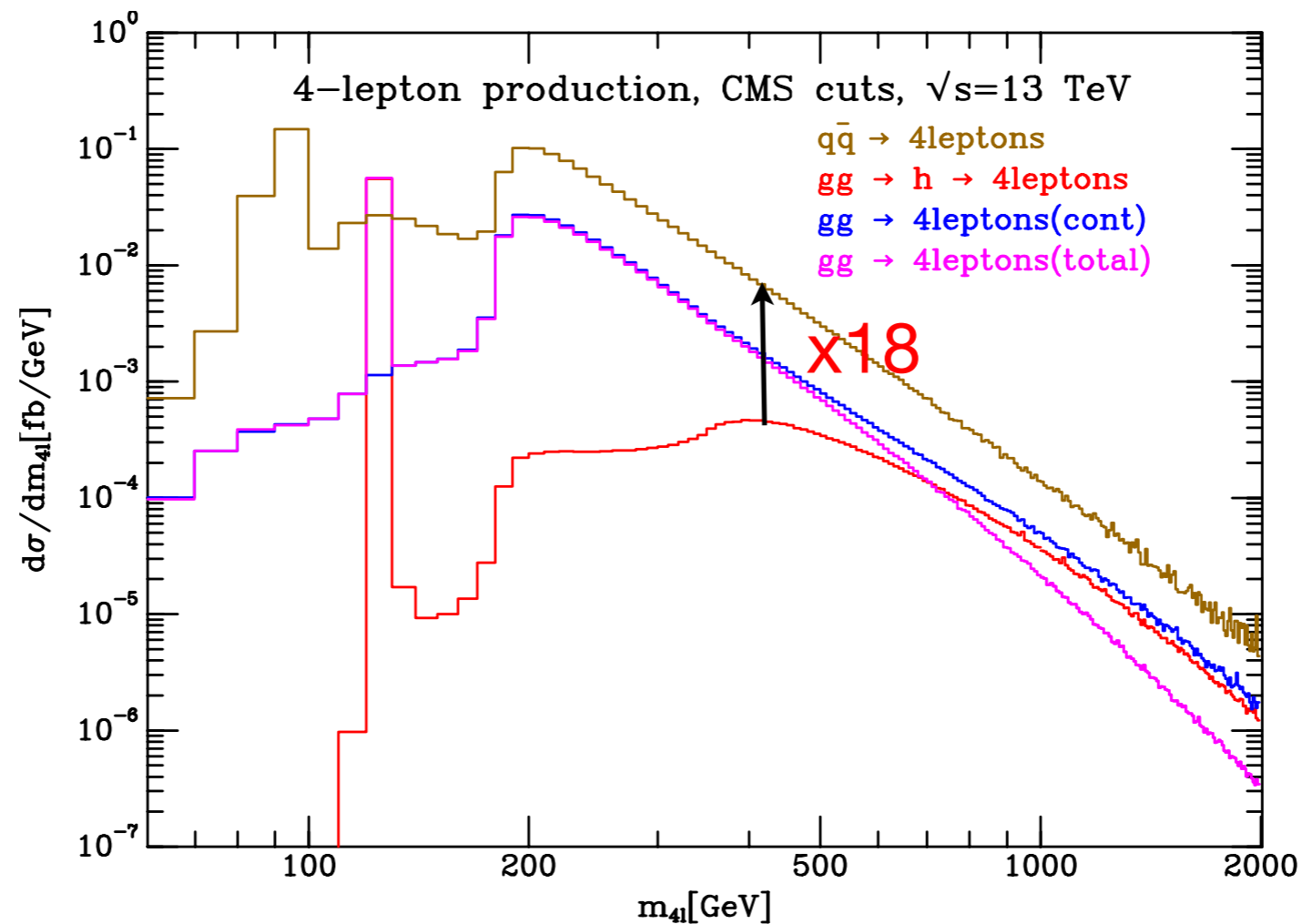
- * Peak at Z mass due to singly resonant diagrams.
- * Interference is an important effect off-resonance.
- * Destructive at large mass, as expected.
- * With the standard model width, Γ_H , challenging to see enhancement/deficit due to Higgs channel.
- * 3 phenomena happening in the tail.

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

CMS cuts
CMS PAS HIG-13-002



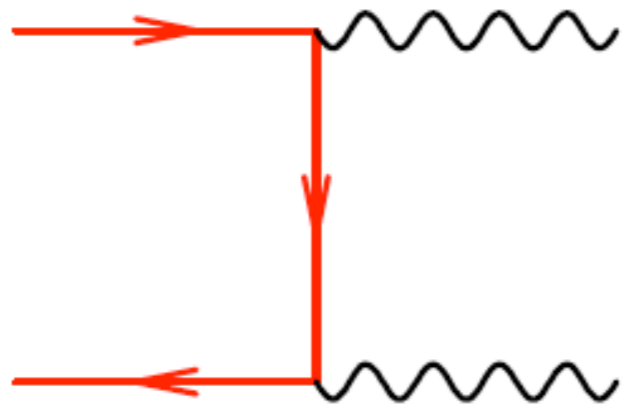
The big picture @ 13 TeV



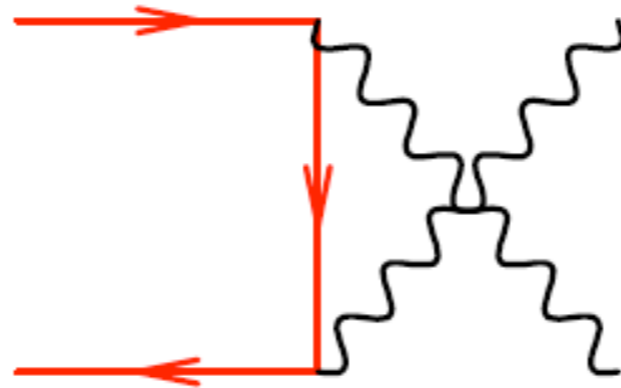
- * $\sigma_{q\bar{q}b}(m_{4l}=400)/\sigma_{gg}^H(m_{4l}=400) \approx 18$ at $\sqrt{s}=13$ TeV
- * (c.f. ~ 30 at $\sqrt{s}=8$ TeV).
- * Higgs off-shell contribution is relatively bigger at higher energy.

Higgs being Higgs

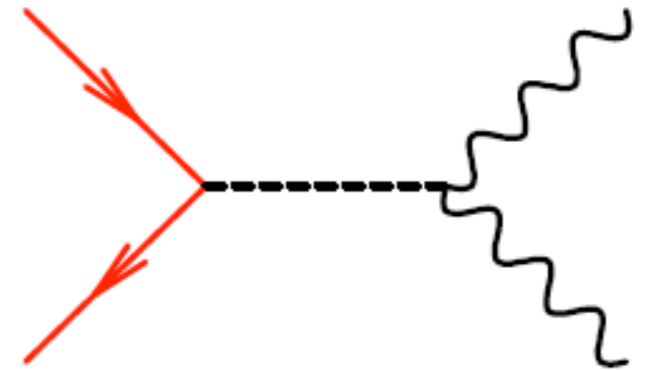
- * Consider right hand side of gluon-gluon initiated diagrams.
- * $tt \rightarrow ZZ$, longitudinal modes of Z-bosons.



$$a_2 E^2 + (b_1 + a_1) m_t E$$



$$-a_2 E^2 + (c_1 - a_1) m_t E$$

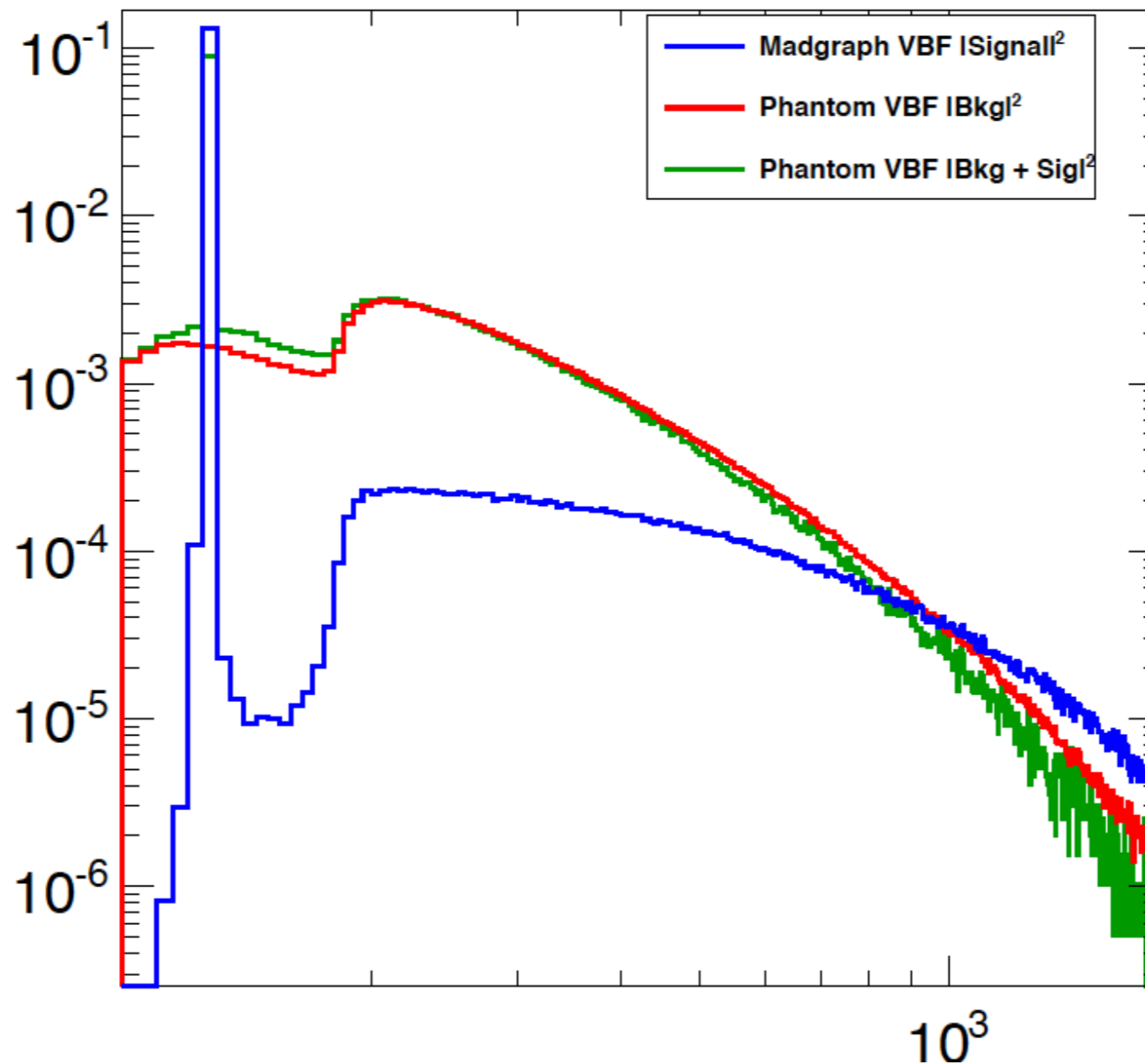


$$-(b_1 + c_1) m_t E$$

- * 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

* $pp \rightarrow \text{jet} + \text{jet} + e^- e^+ \mu^- \mu^+$



Caola-Melnikov method for Higgs width

- * Higgs cross section under the peak, section depends on 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).

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

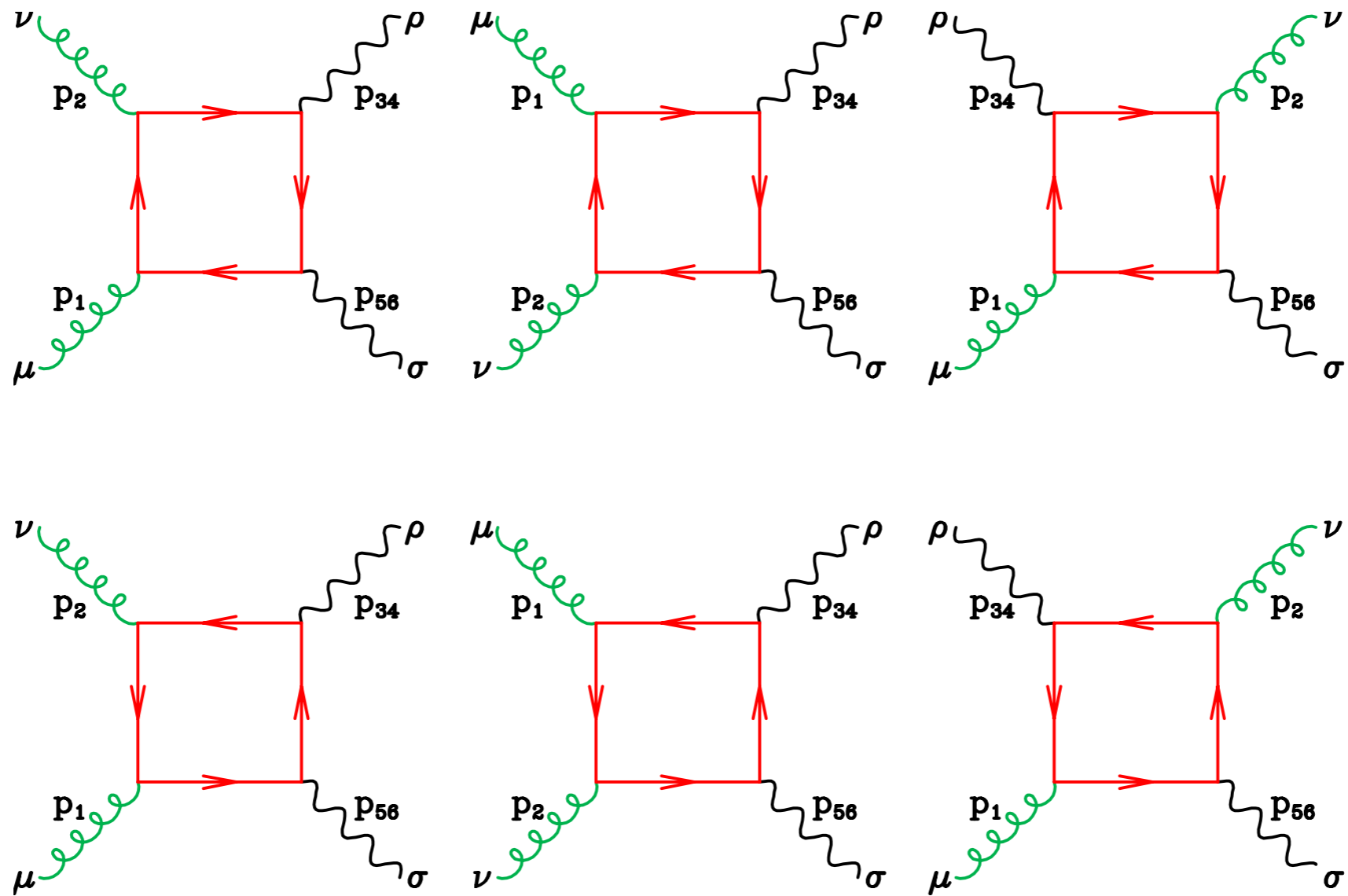
- * Taking ratio
$$\frac{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{experimental gg}}}{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{theoretical SM}}} = \frac{\Gamma}{\Gamma^{\text{SM}}}$$

- * Ratio depends linearly on the Higgs boson width.

Caola-Melnikov 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 $gg \rightarrow Z/g^* + Z/g^*$ (background)



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

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

- * 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

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

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

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

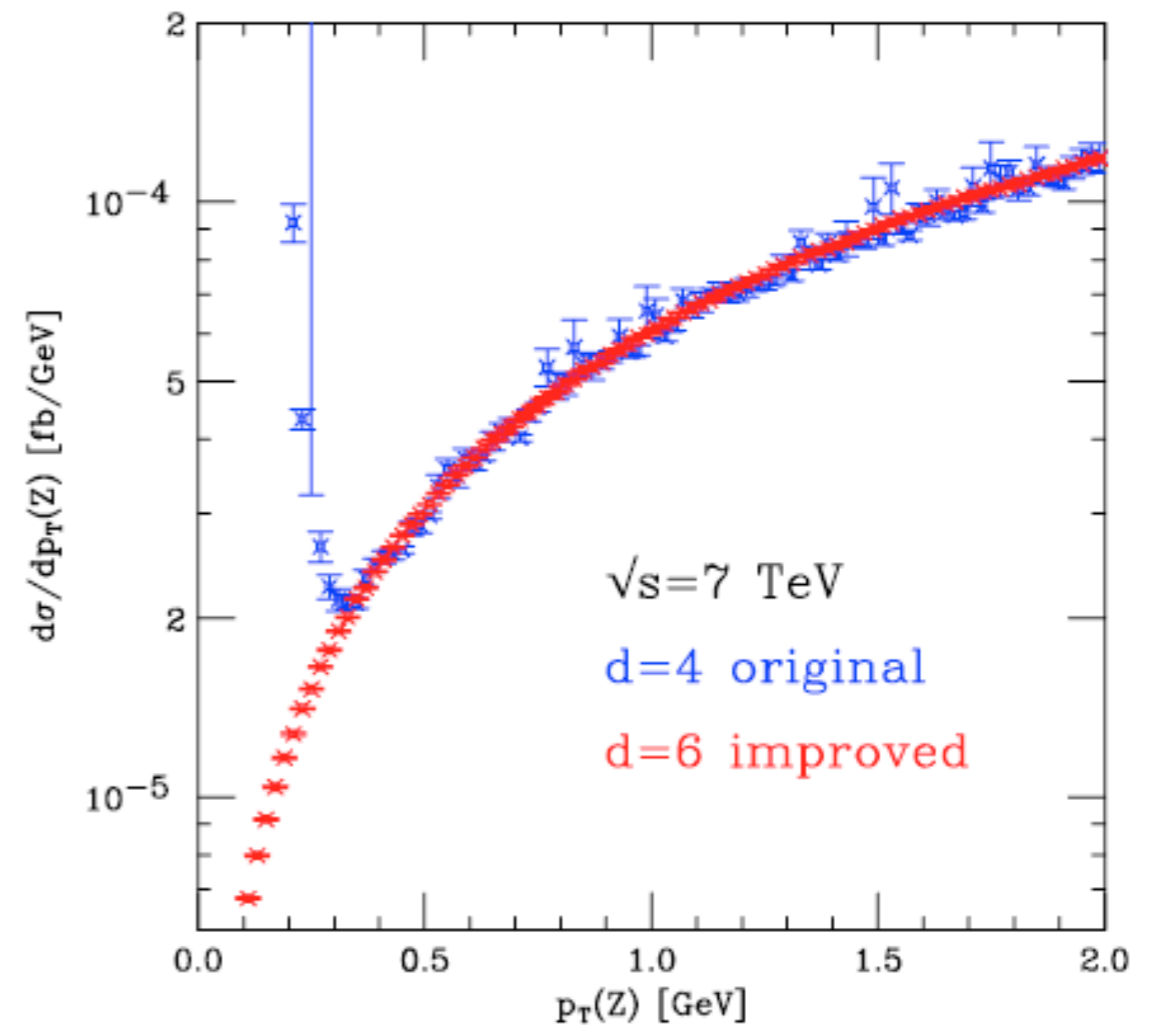
- * Relatively simple formulae for each presented in paper.

$P_T=0$

- * Translating back to Bjorken-Drell notation,

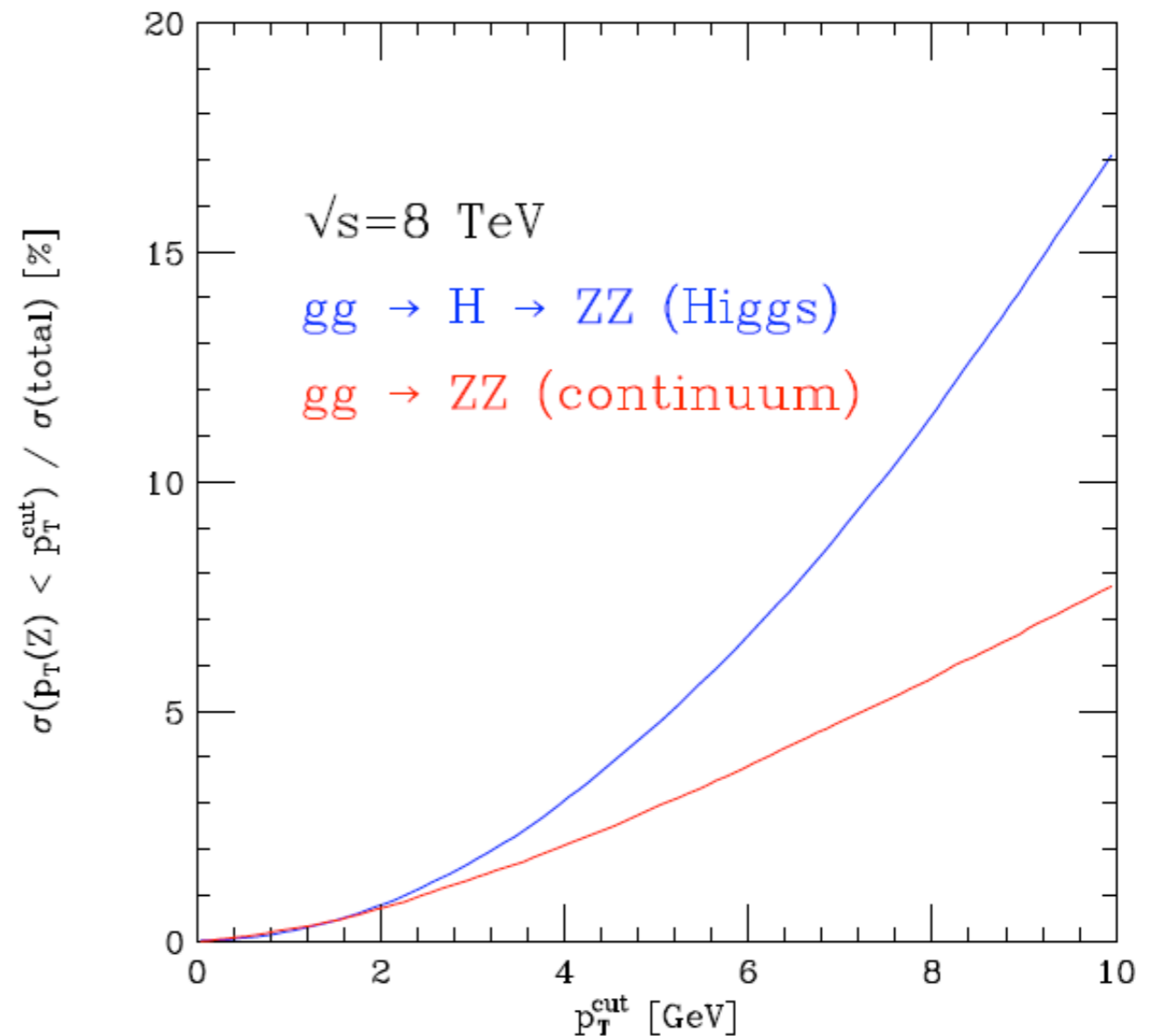
$$\langle 2|(3+4)|1\rangle = \bar{u}_-(p_2)(\not{p}_3 + \not{p}_4)u_-(p_1)$$

- * Singular when 3+4 is a linear combination of 1 and 2.
- * Pernicious in this case, because we cut on 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.



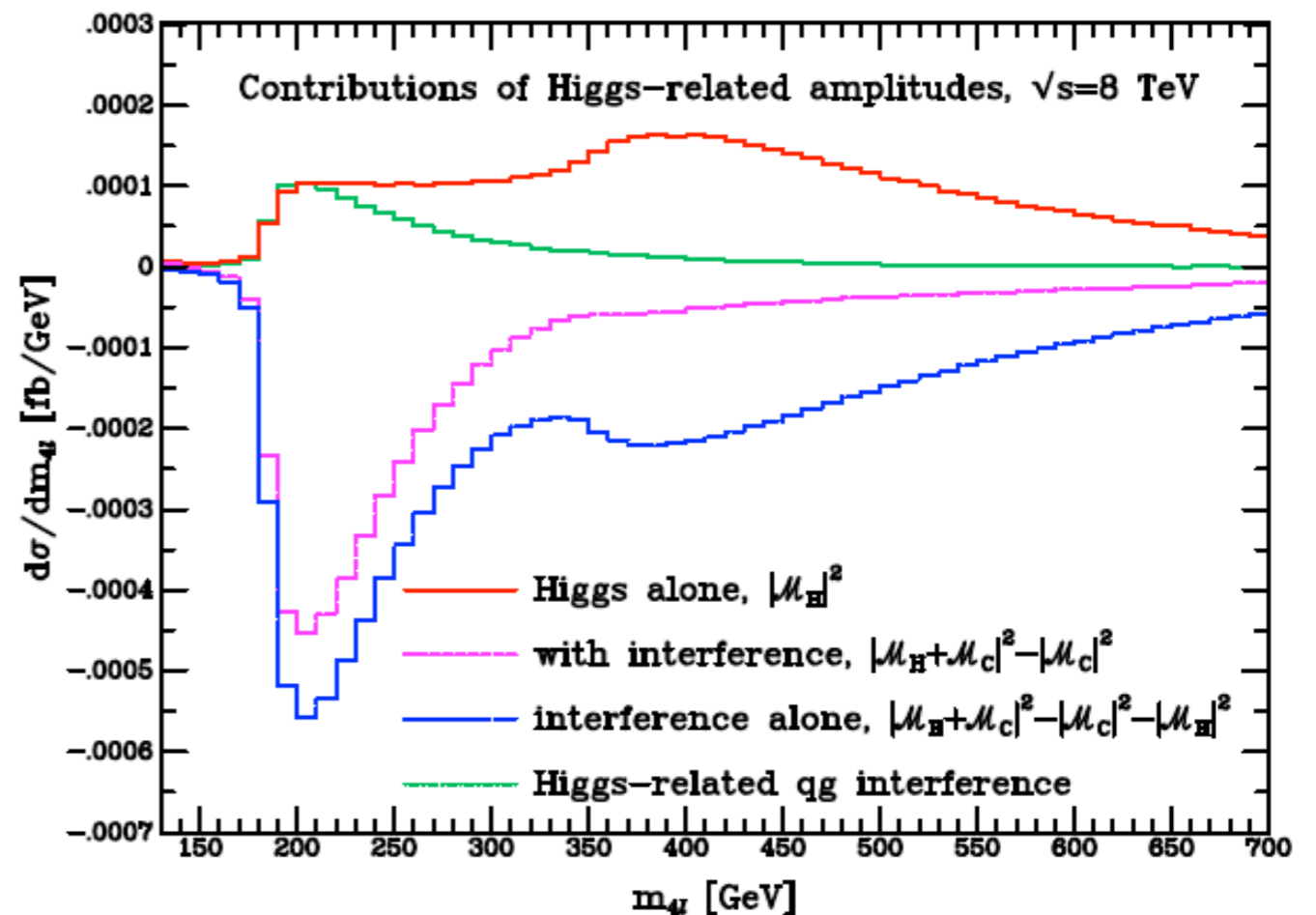
Why not just cut out the low p_T region?

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



Size of interference @ 8 TeV

- * Impossible to predict correct rate in the $m_{4l} > 200 \text{ GeV}$ 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 $m_{4l} > 300 \text{ GeV}$



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 $\sigma_{off} \equiv \sigma_{off}^H + \sigma_{off}^{int}$ at 8TeV.

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

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

- * 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).

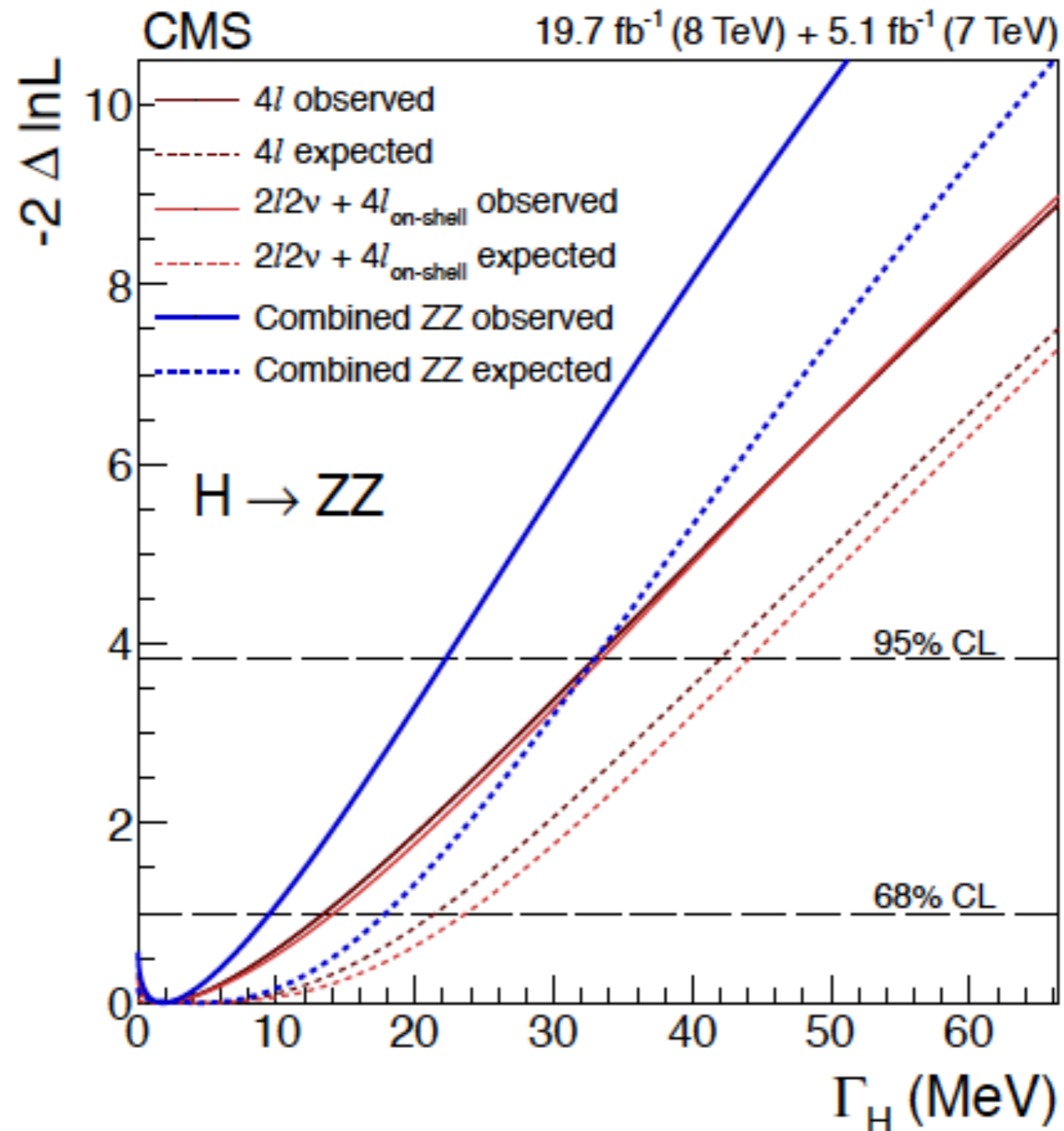
$$N_{off}^{4\ell}(m_{4\ell} > 130 \text{ GeV}) = 2.78 \left(\frac{\Gamma_H}{\Gamma_H^{SM}} \right) - 5.95 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

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

CMS result

arXiv:1405.3455

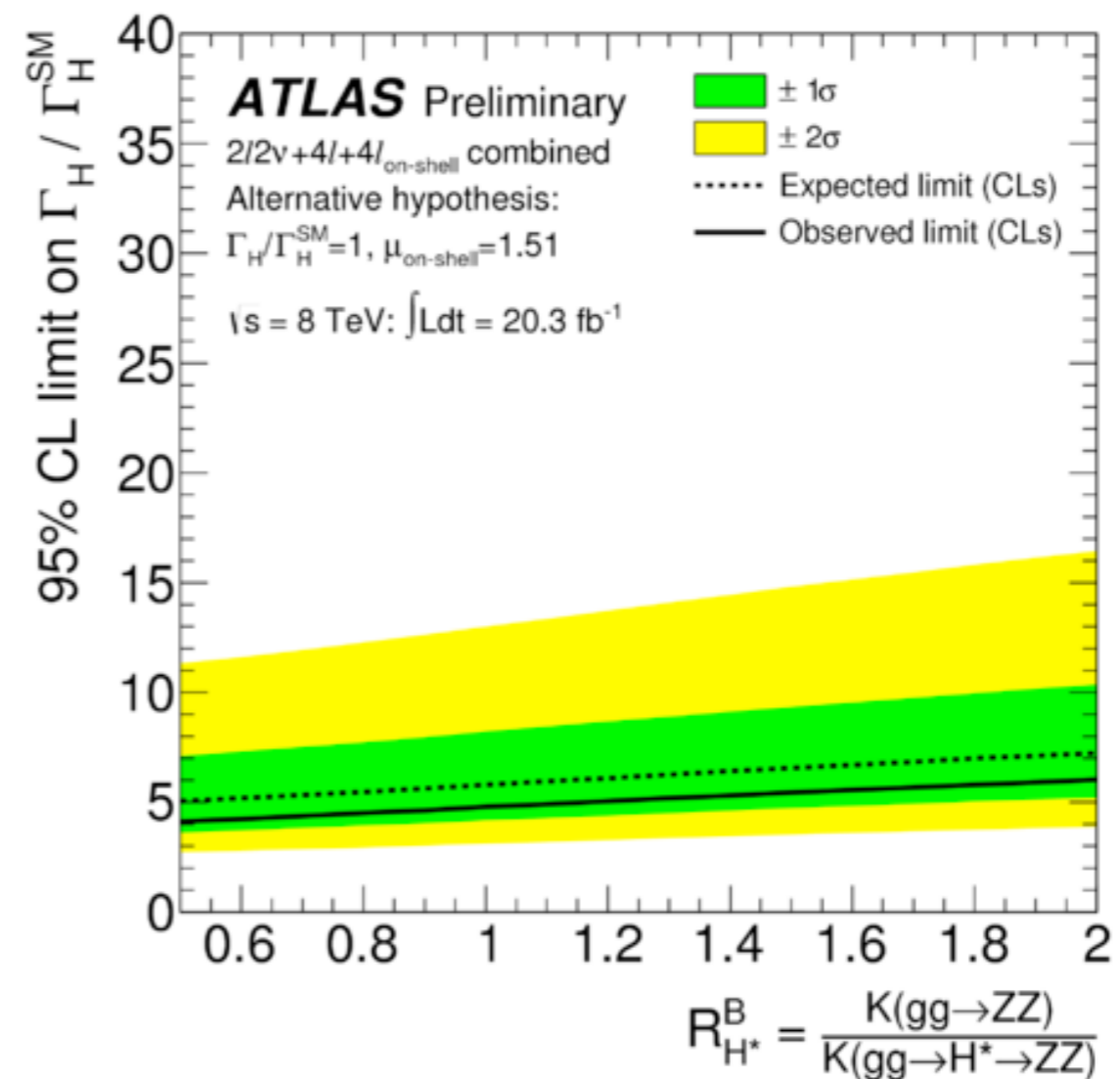
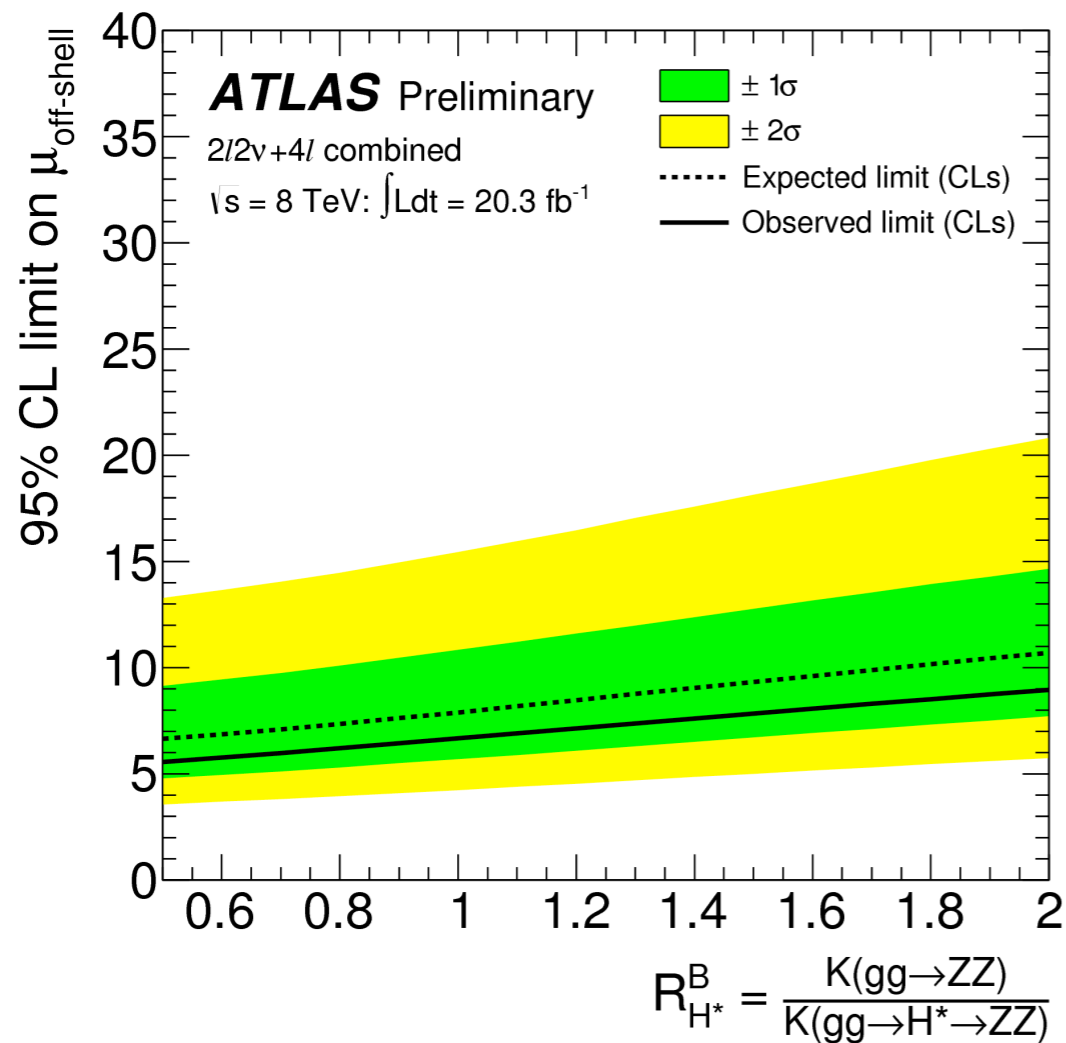
* $\Gamma_H/\Gamma_H^{\text{SM}}=5.4$ at 95%cl



ATLAS result

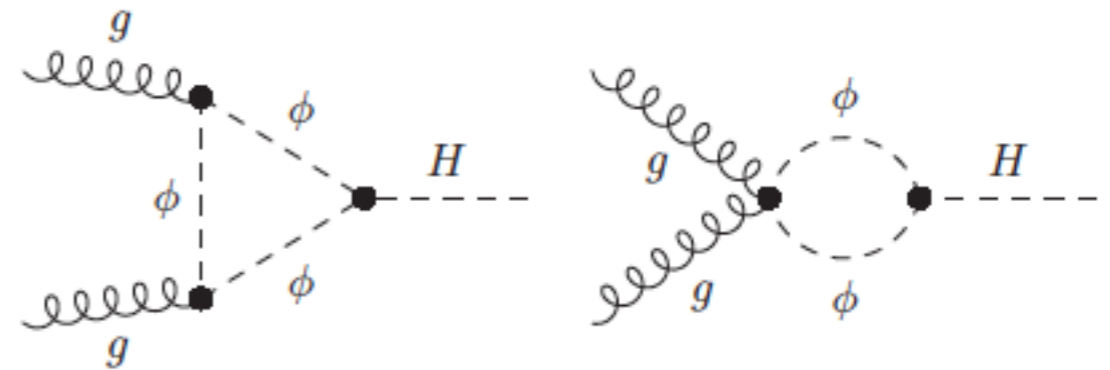
ATLAS-CONF-2014-042

- * Result for both off-shell coupling and width as a function of relative K-factor
- * $\Gamma_H/\Gamma_H^{\text{SM}}=4.8/7.7$ 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 $\sim 70\text{GeV}$.
- * This gives a potentially large contribution to $gg \rightarrow h$ which will have to be compensated to give $\mu=1$ 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.

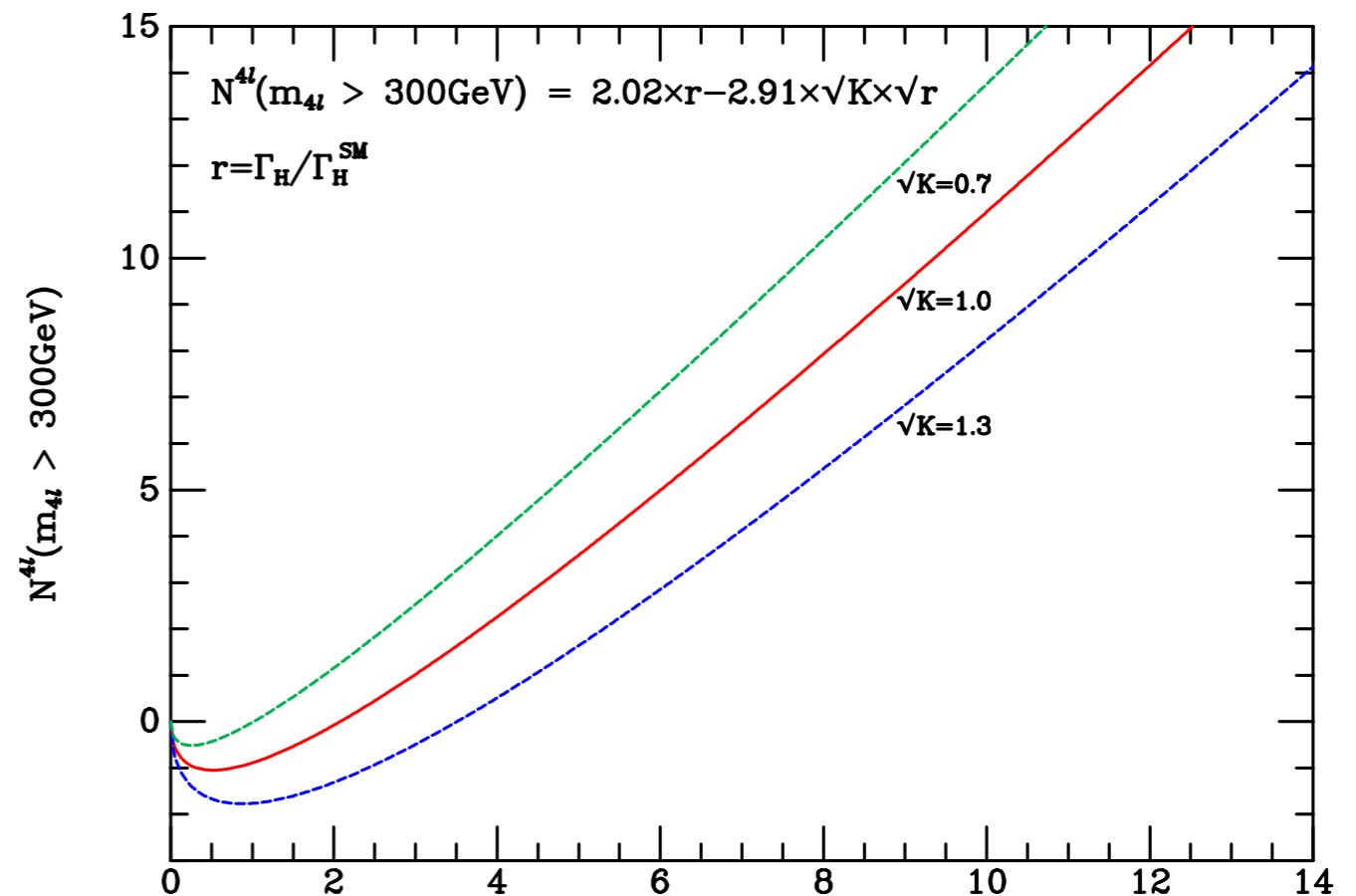


Englert and Spannowsky, 1405.0285

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 $K=1$?

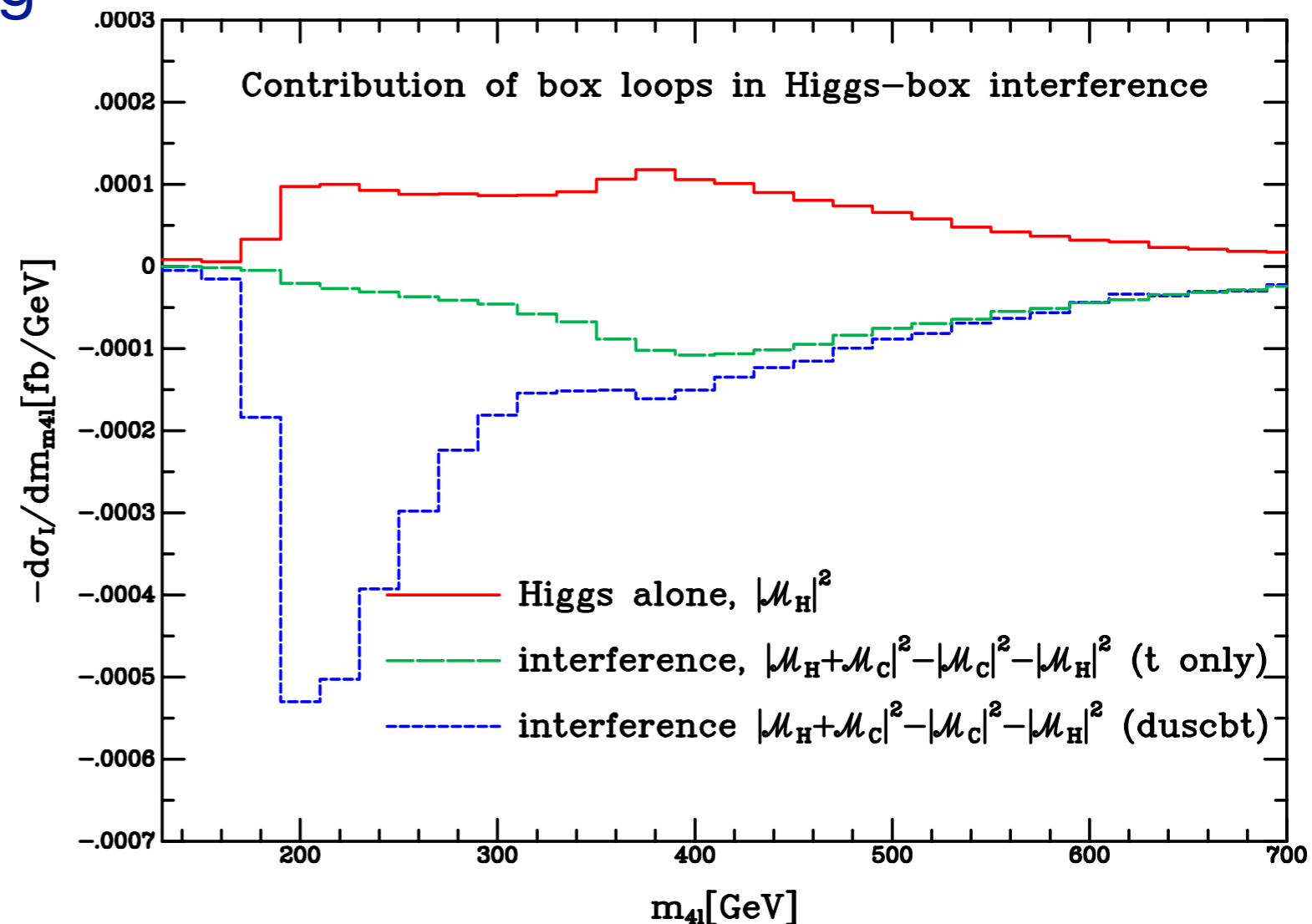
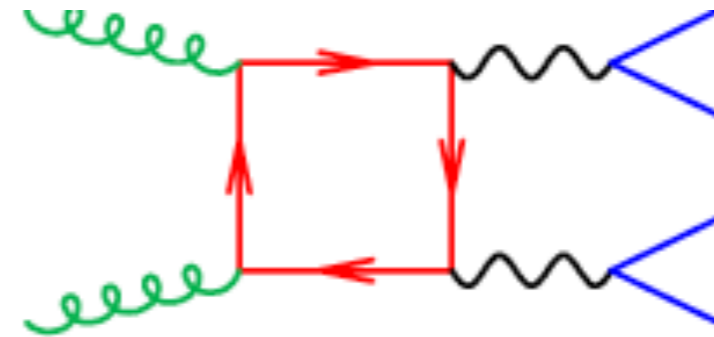
- * K factor estimated in the soft gluon limit for $H \rightarrow WW$ and $M_H=600\text{GeV}$

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 $m_{4l} > 400\text{GeV}$.



K=1 (continued)

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

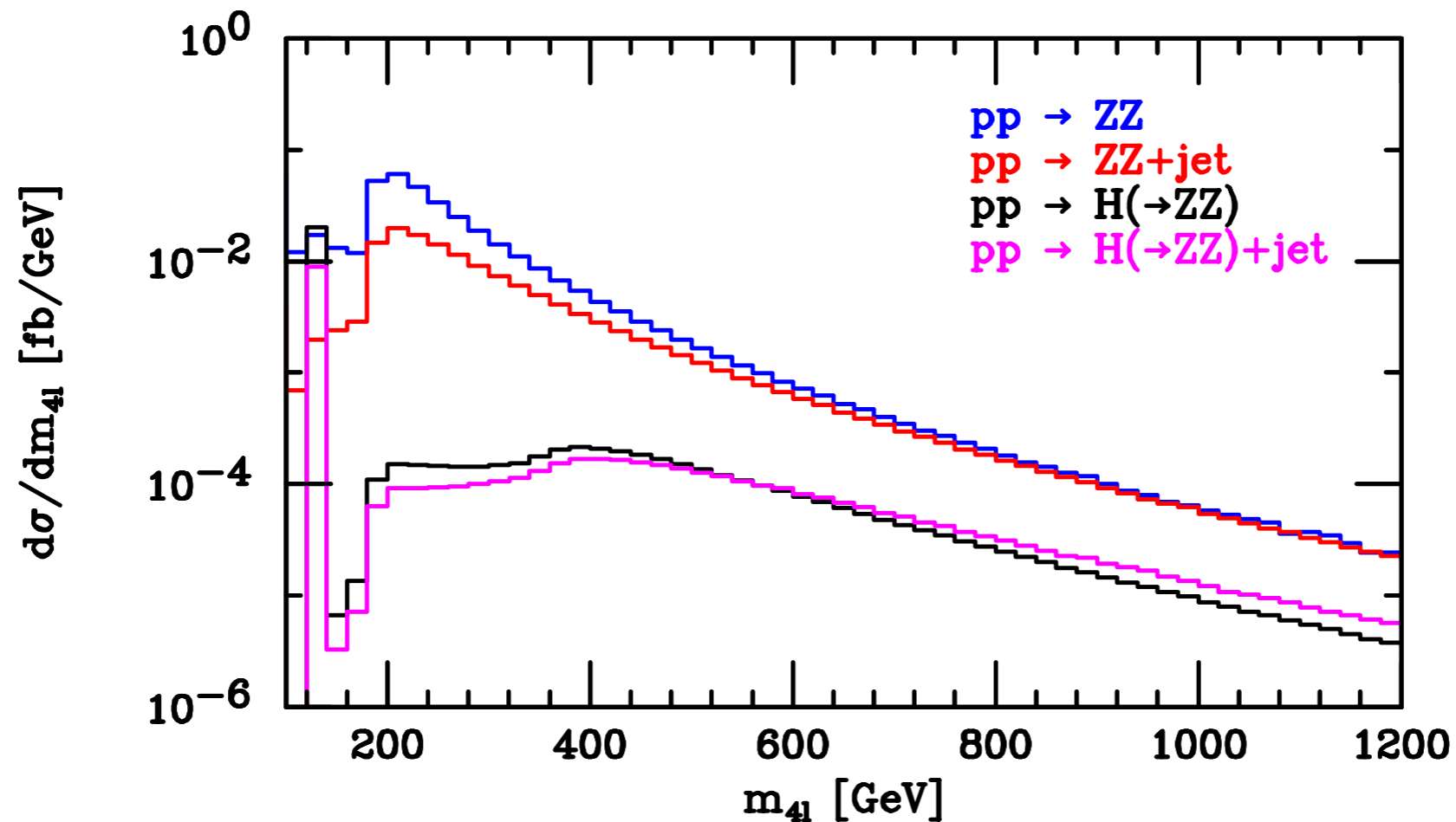
$$K \simeq 1 + \frac{\alpha_s}{2\pi} (2\pi^2 + c_1)$$

- * 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 $\sim 6\%$ for $M_H=600\text{GeV}$ where the interference is a $+15\%$ effect
- * Variation of c_1 can have a larger effect in our case, (perhaps $\sim 30\%$) 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 $ZZ + \text{jet}$.

Interference effects in ZZ+jet production

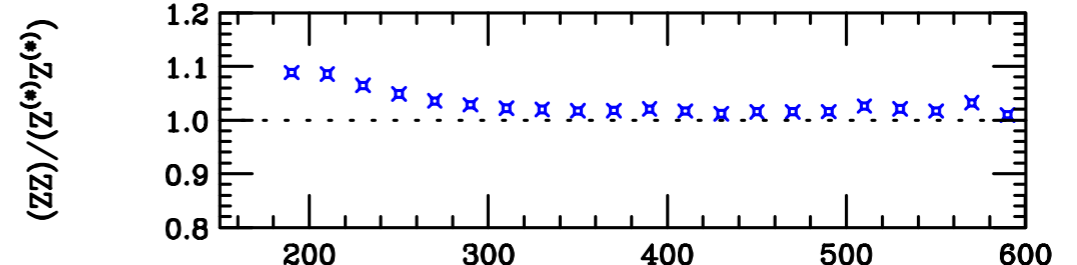
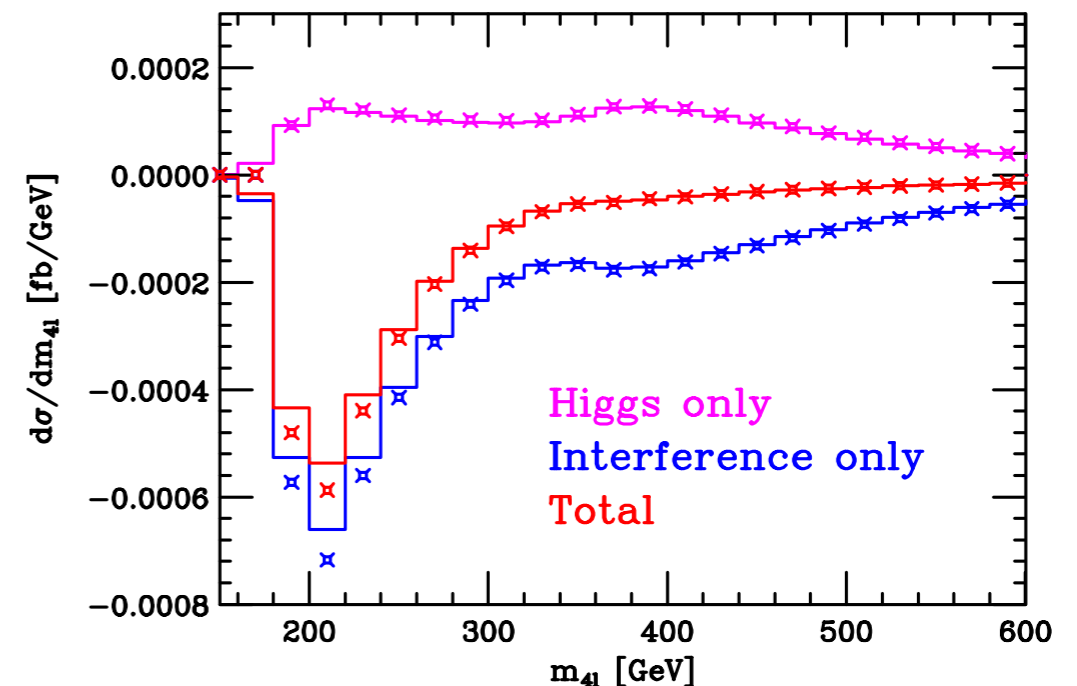
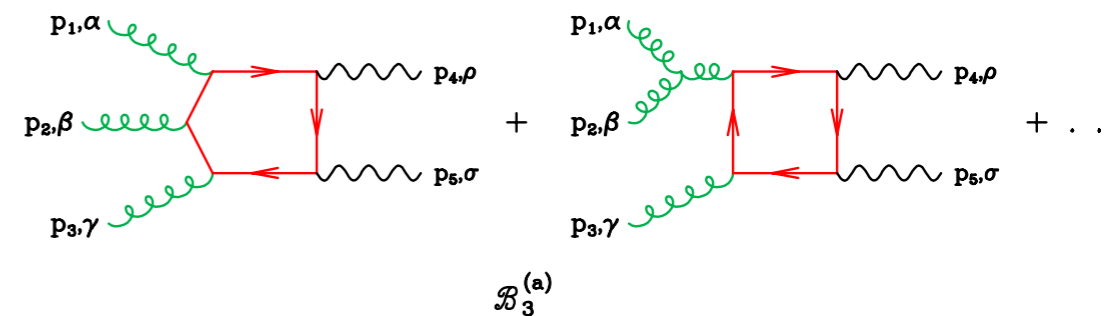
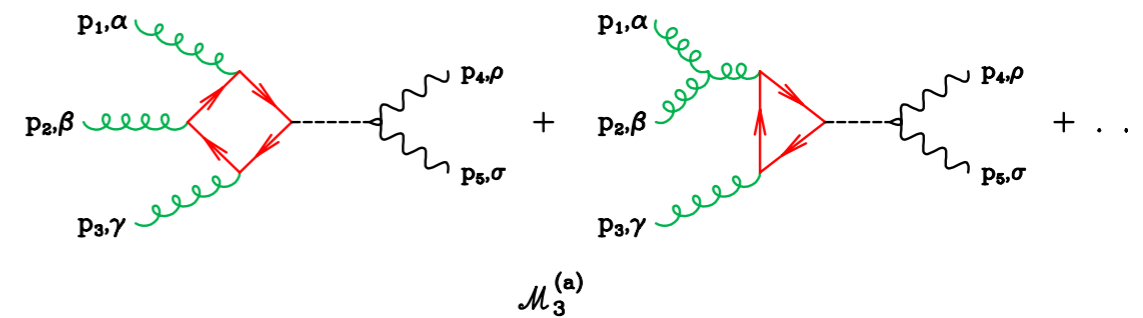
- * Better signal to background ratio in the ZZ+jet channel.



- * For $m_{4l} > 300$ GeV,
Higgs rate in 1-jet bin \sim 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:

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

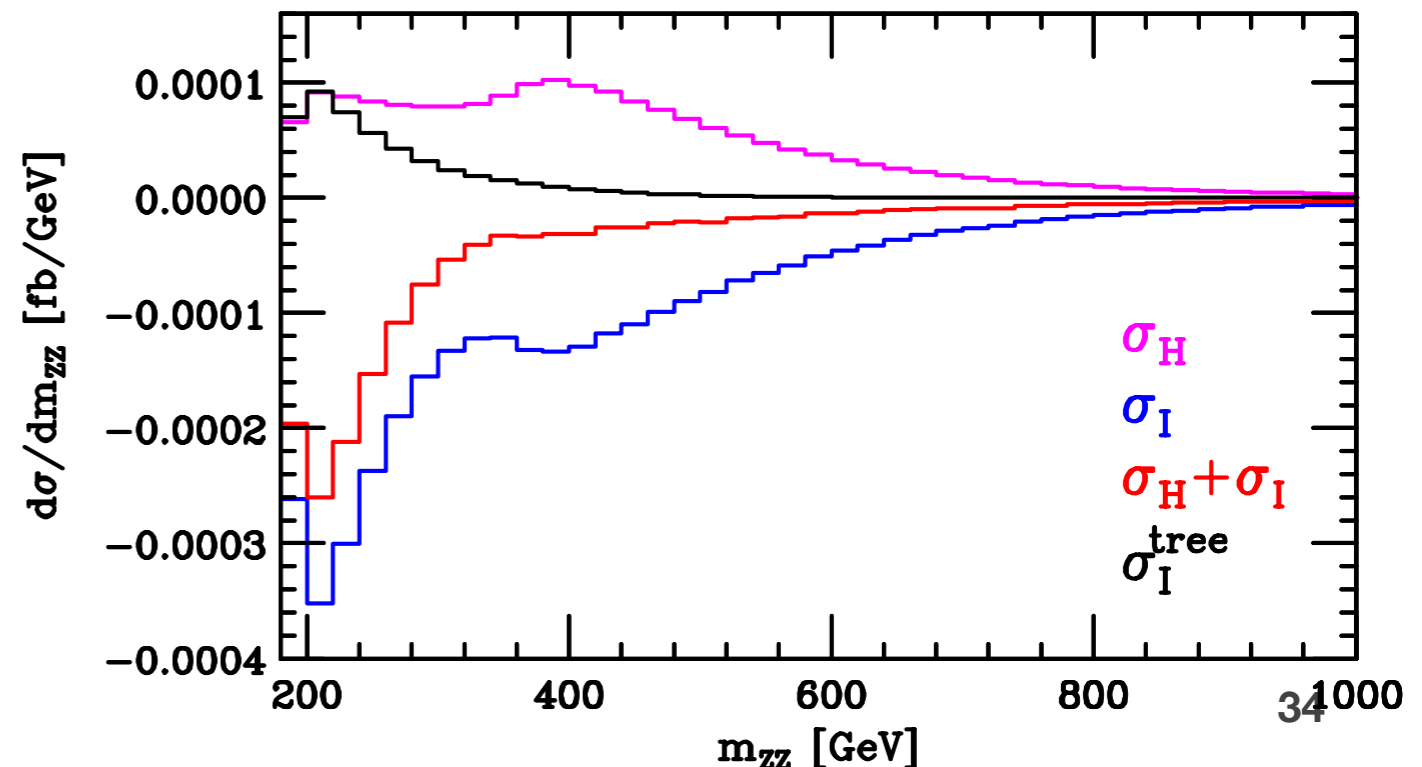
- * ZZ result withouts fiducial cuts on leptons:

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

- * ZZ+jet result ($p_T(\text{jet}) > 30 \text{ GeV}$, no cuts on leptons)

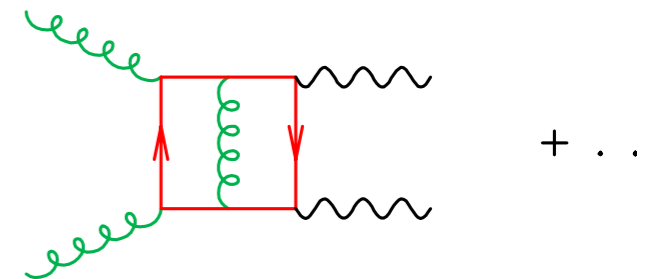
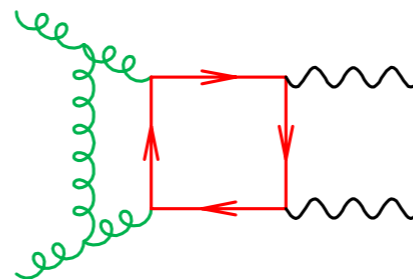
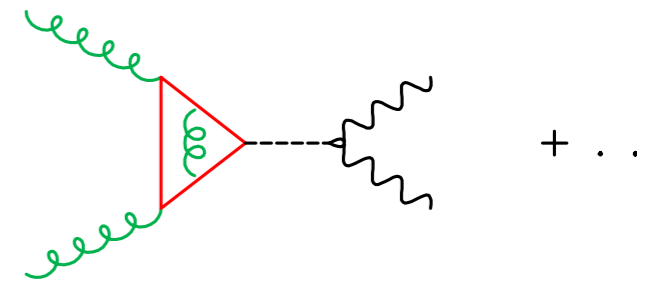
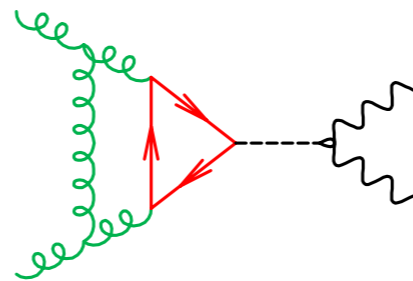
$$\sigma_{off,ZZ+\text{jet}}^{H+I}(m_{ZZ} > 300 \text{ GeV}) = 0.0280 \left(\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} \right) - 0.0392 \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}} \text{ fb},$$

- * 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 on (potential) current bounds on Higgs width

* Measurement methods,

* Width convoluted with resolution

* Mass shift in $\gamma\gamma$ mode due to interference (Martin 1208.1533, 1303.3342, de Florian et al, 1303.1397, Dixon-Li 1305.3854)

* Comparison of on-shell-off-shell rate (CM method)

* Other methods involve theoretical assumptions, typically that the Higgs coupling to electroweak vector bosons does not exceed the SM value, (eg. Dobrescu, Lykken, 1210.3342 and CMS PAS HIG-13-005, $\Gamma_H / \Gamma_H^{SM} < 2.8$)

Method	Measured quantity	Γ_H [MeV]	Γ_H / Γ_H^{SM}
CMS-PAS-HIG-13-016	Width \times resolution	< 6900	< 1600
1312.1628 (CEW)	Off-peak/on-peak WW , $m_T > 130, 300$	$< 500 - 180$	$< 125, 45$
1311.3589 (CEW)	Off-peak/on-peak ZZ , $m_{4l} > 130, 300$, MEM	$< 170, 100, 60$	$< 43, 25, 15$
1305.3854 (Dixon-Li)	Higgs mass in $\gamma\gamma$,	< 800	< 200

Experiments have bettered the predictions for the CM methods.

Summary

- * With 3ab^{-1} , mass shift in $\Upsilon \Upsilon$ will lead to an expected limit on width of $15\Gamma_{\text{SM}}$.
- * MCFMv6.8 is a fast code for $gg \rightarrow ZZ \rightarrow 4l$ 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 determining the 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 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 $Z/\gamma^* Z/\gamma^* \rightarrow e^-e^+\mu^-\mu^+$ process.
- * $ZZ+\text{jet}$ 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 $p_T < 7 \text{ GeV}$, for continuum related pieces.
- * Our fiducial cross sections are:-

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

Energy	σ_{peak}^H	$\sigma_{off}^H(m_{4l} > 300 \text{ GeV})$	$\sigma_{off}^{int}(m_{4l} > 300 \text{ GeV})$
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 $\sigma^{\text{peak}}(13\text{TeV}) \approx 2 \sigma^{\text{peak}}(8\text{TeV})$ whereas $\sigma^{\text{off-peak}}(13\text{TeV}) \approx 3 \sigma^{\text{off-peak}}(8\text{TeV})$, so method will improve with energy.

- * 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 $ZZ \rightarrow e^-e^+e^-e^+, \rightarrow \mu^-\mu^+\mu^-\mu^+$
 - * Addition of interference $ZZ \rightarrow e^-e^+\nu_e\nu_e, W^-W^+ \rightarrow e^-\nu_e e^+\nu_e$
 - * 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.

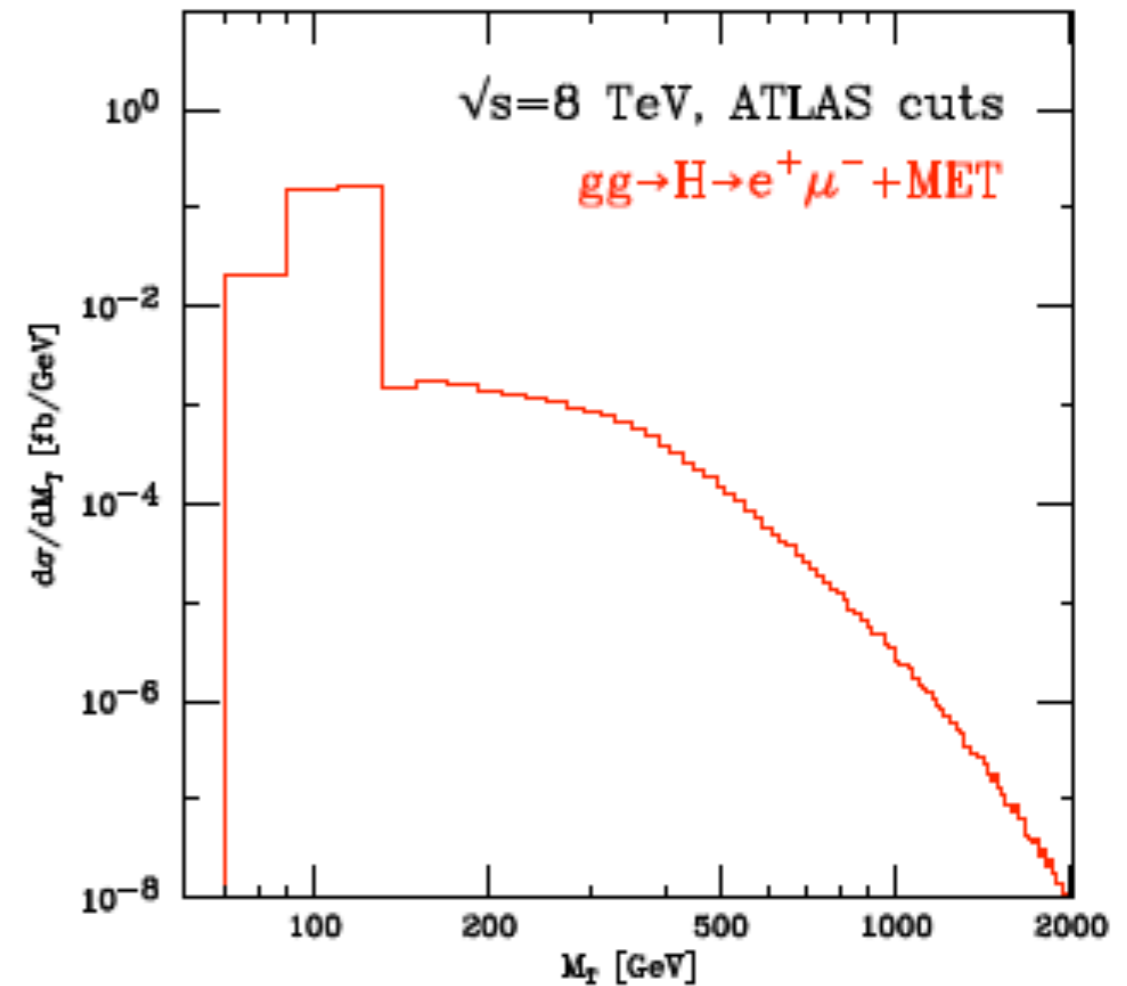
WW

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 $gg \rightarrow W^+W^- \rightarrow e^+\mu^- \nu_e \nu_\mu$
- * 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

$$\text{Br}(H \rightarrow WW) \times \text{Br}(W \rightarrow \ell\nu)^2 = 2.7 \times 10^{-3}$$

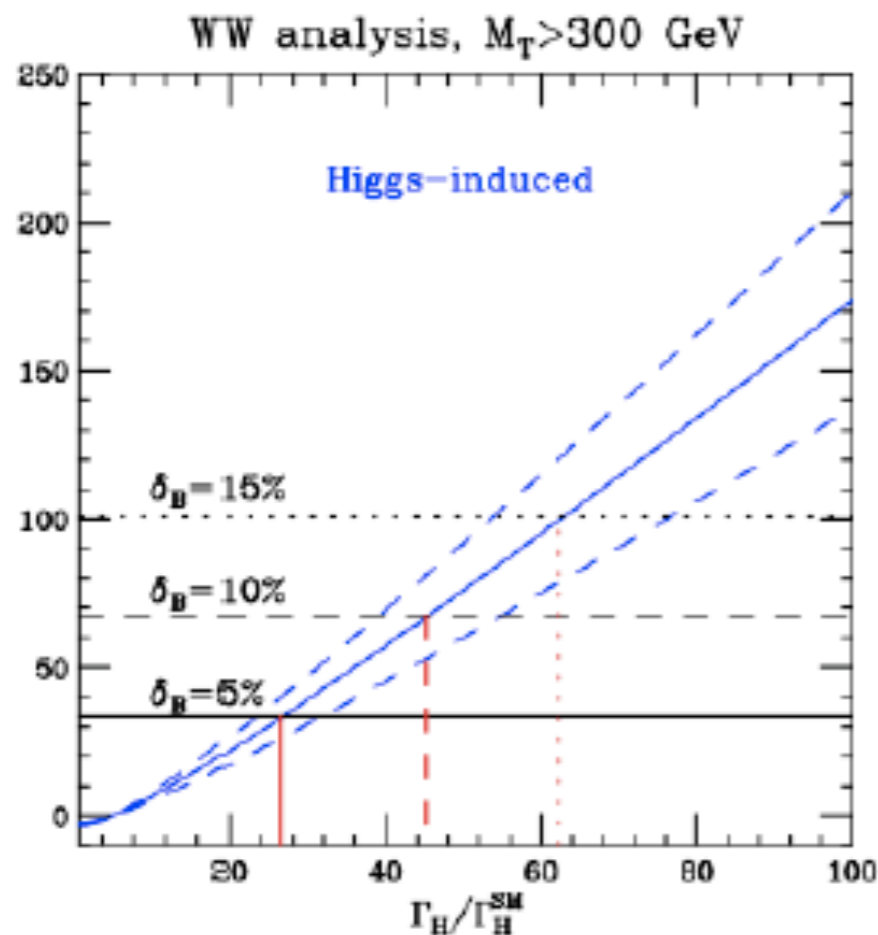
$$\text{Br}(H \rightarrow ZZ) \times \text{Br}(Z \rightarrow \ell^+\ell^-)^2 = 3.2 \times 10^{-5}$$

* 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.



- * $\langle B \rangle = 336$ events
- * Try to be conservative by using systematic uncertainty on theory and choice of experimental systematics.

$$\Gamma_H < 45^{+9}_{-7} \Gamma_H^{\text{SM}}$$

- * Different flavor $e\mu$, 20fb^{-1} , $\delta_B = 10\%$

Interference effects in $\Upsilon\Upsilon$

Dixon-Siu hep/ph0302233

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

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

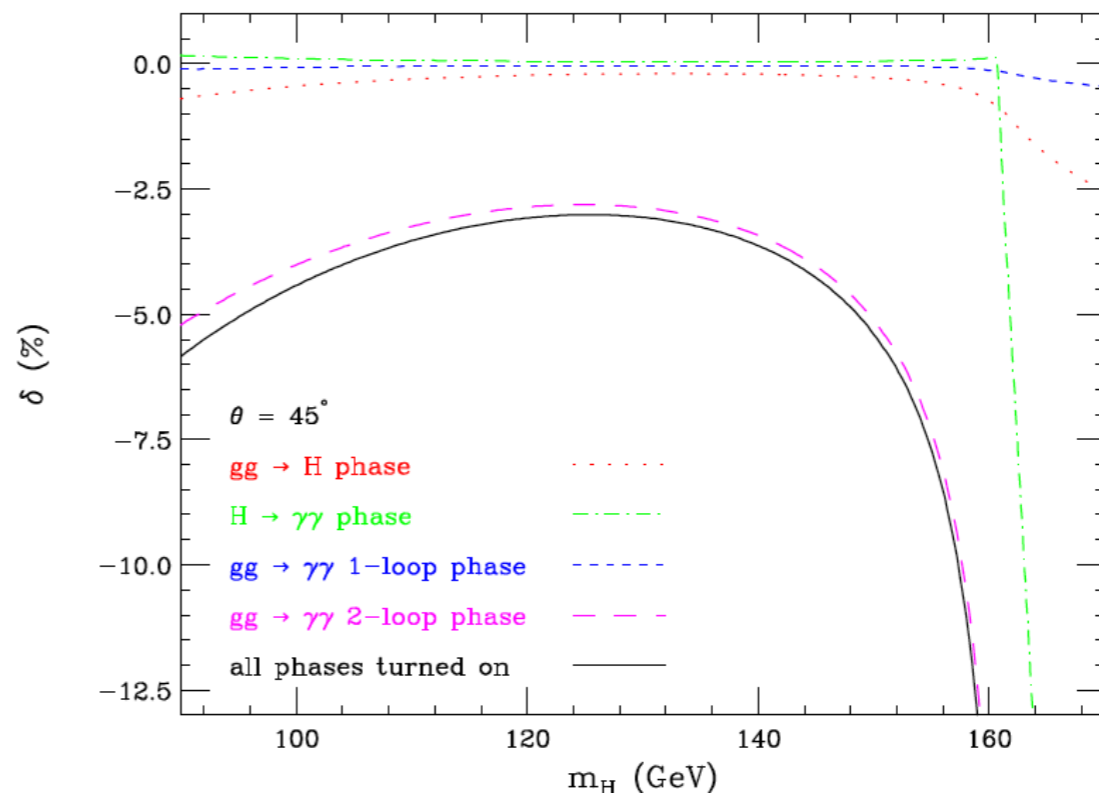
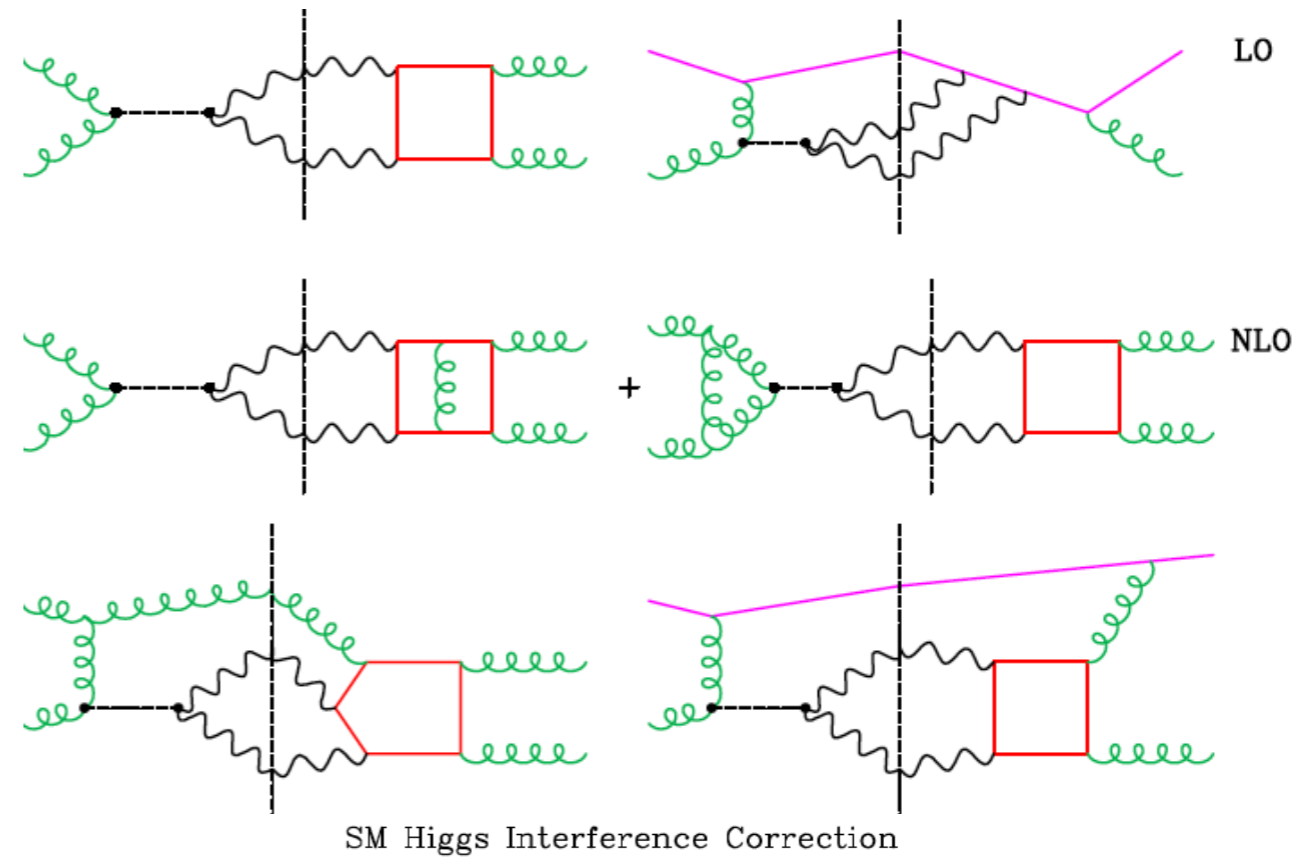
- * The interference term can be written as a sum of 2 terms:

$$\begin{aligned} & -2(\hat{s} - m_H^2) \frac{\text{Re}(\mathcal{A}_{gg\rightarrow H}\mathcal{A}_{H\rightarrow\gamma\gamma}\mathcal{A}_{cont}^*)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \quad * \text{ averages to zero, shifts apparent mass} \\ & -2m_H\Gamma_H \frac{\text{Im}(\mathcal{A}_{gg\rightarrow H}\mathcal{A}_{H\rightarrow\gamma\gamma}\mathcal{A}_{cont}^*)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2} \quad * \text{ changes peak height} \end{aligned}$$

- * Experimental resolution averages over line-shape.

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

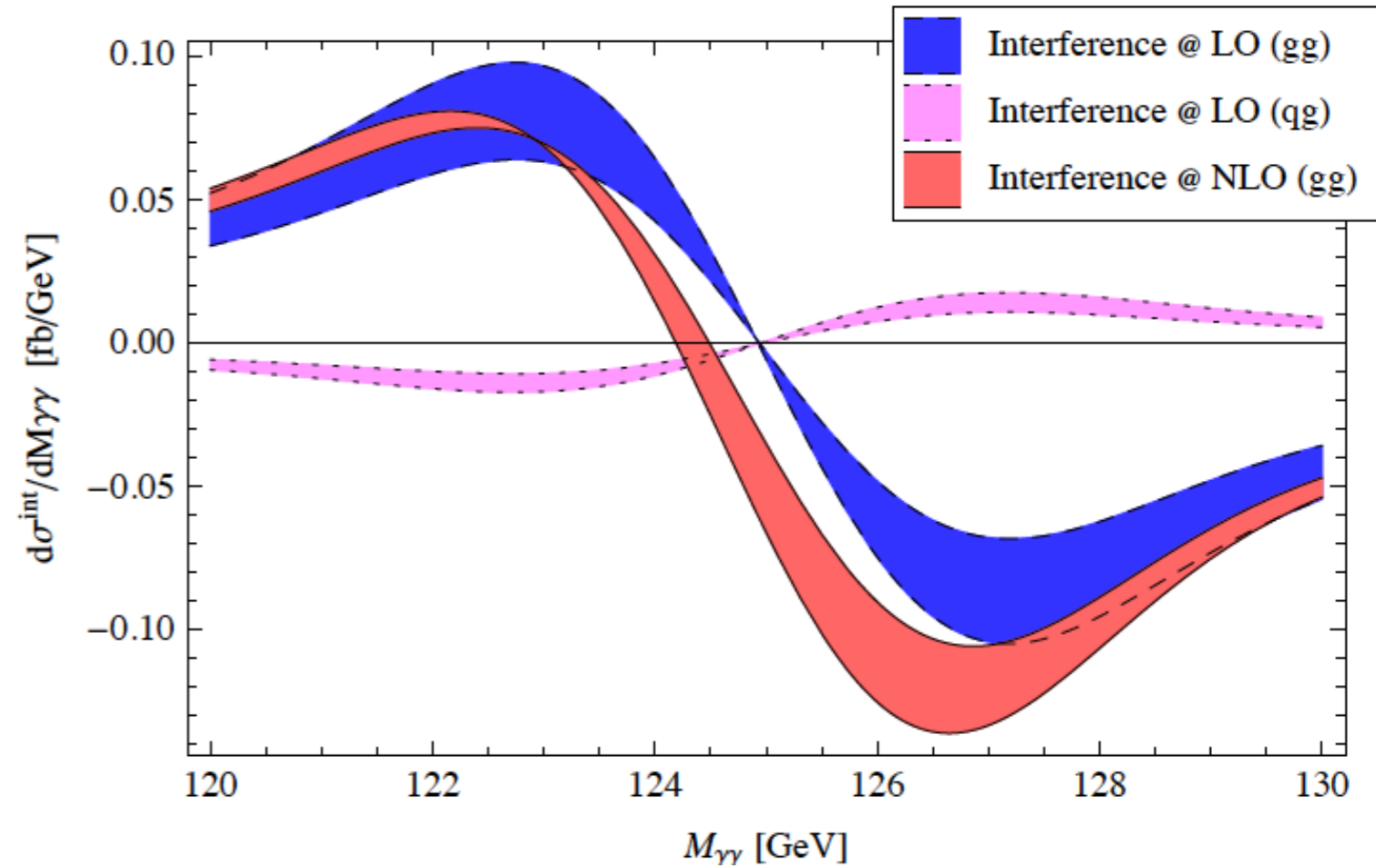
- * One-loop contribution vanishes for $m_q \rightarrow 0$ because of helicity suppression for like helicities.
- * Dominant term comes from two loops.
- * Interference is destructive and of order 5%.



Interference effects in $\Upsilon\Upsilon$ (real part)

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

- * Gaussian smeared interference contribution, ($\sigma=1.7\text{GeV}$)
- * Apparent mass shift for inclusive production at NLO is about 70MeV
- * Significantly less than $\text{LO}\simeq 120\text{MeV}$.
- * Needs to be repeated with real experimental resolution.



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 $200\Gamma_{\text{SM}}$

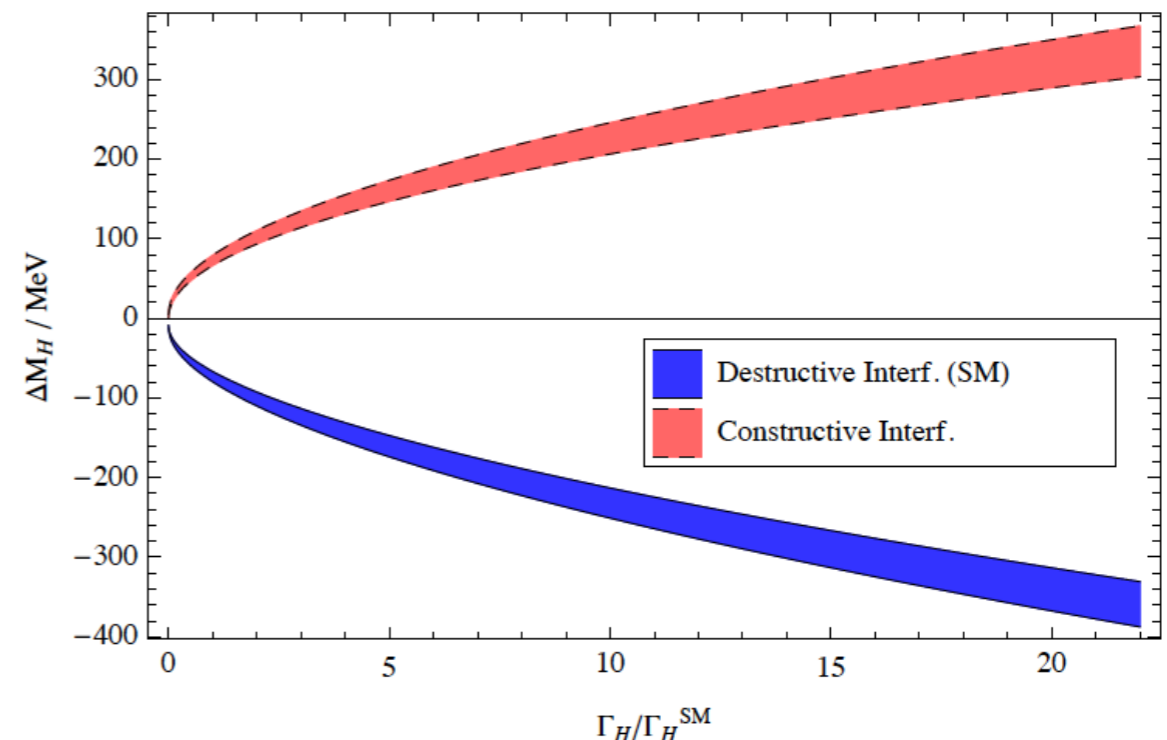
- * ATLAS: $m_{H^{\gamma\gamma}} - m_{H^{4l}} = +1.47 \pm 0.72 \text{ GeV}$

arXiv:1406.3827

- * CMS: $m_{H^{\gamma\gamma}} - m_{H^{4l}} = -0.87^{+0.54}_{-0.59} \text{ GeV}$

CMS-PAS_HIG-14-009

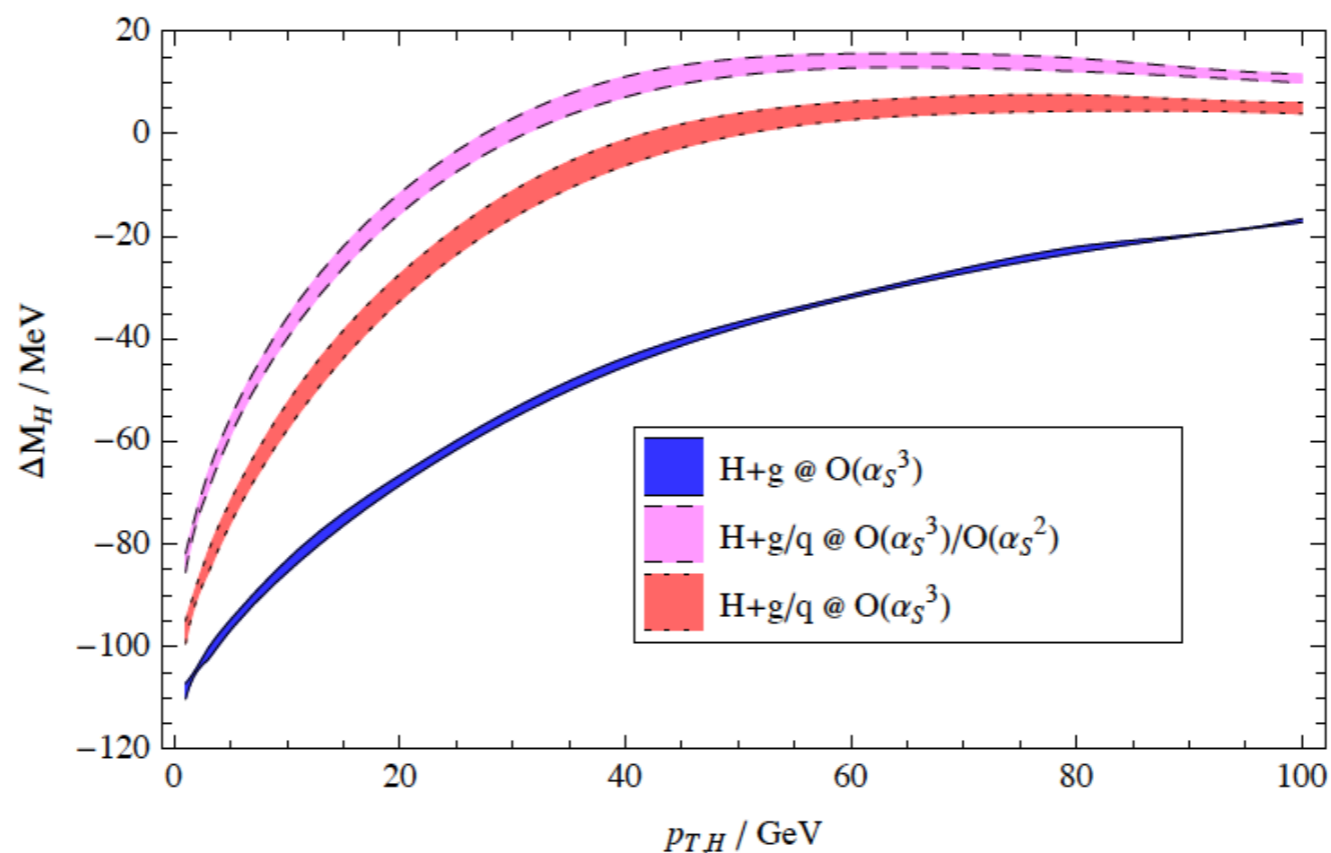
- * Ultimately with 3ab^{-1} one can achieve $\Delta m_H \sim 100 \text{ MeV}$, leading to a bound of $15\Gamma_{\text{SM}}$ at 95%cl.



Reference masses

- * ZZ(4-lepton) mass, (M_{ZZ} mass shift negligible)
- * $\gamma\gamma$ mass at high p_T :with a cut at $\sim 30\text{GeV}$, there is no mass shift.

Martin 1303.3342, Dixon-Li 1305.3854



- * $\gamma\gamma$ mass in vector boson fusion