"Interference, line shape theory" or Bounding the Higgs width at LHC

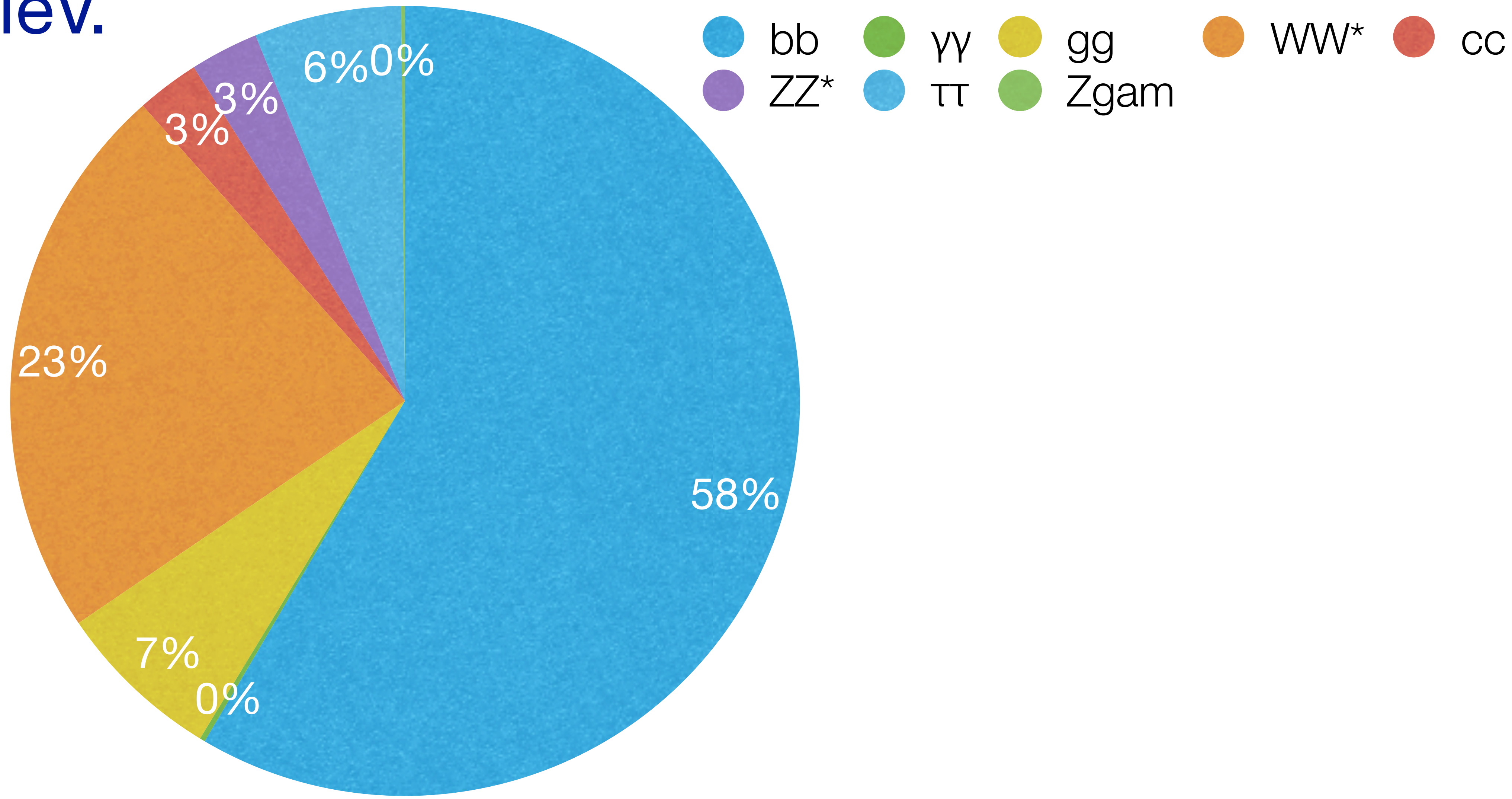
Higgs Hunting, 22 July 2014

Keith Ellis, Fermilab

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

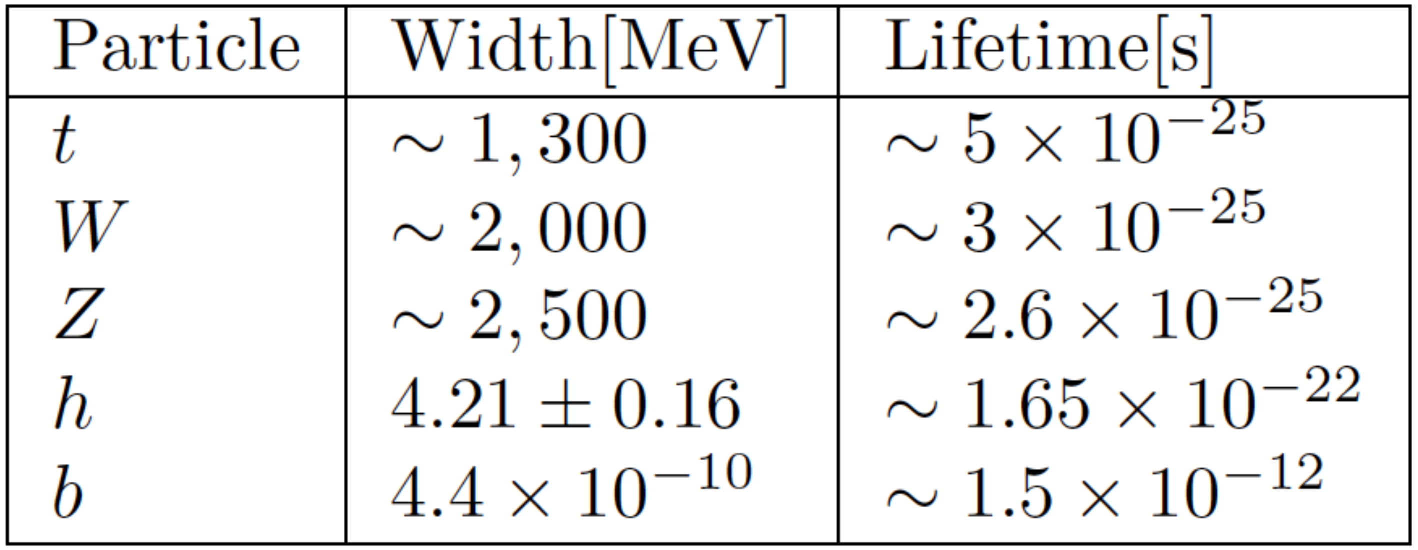
Higgs boson branching fractions

- Large number of observable SM Higgs decays
- We will consider ɣɣ,WW*,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 ɣɣ

Dixon-Siu hep/ph0302233

- Resonance-continuum interference effects are normally small for a narrow resonance.
- ɣɣ 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

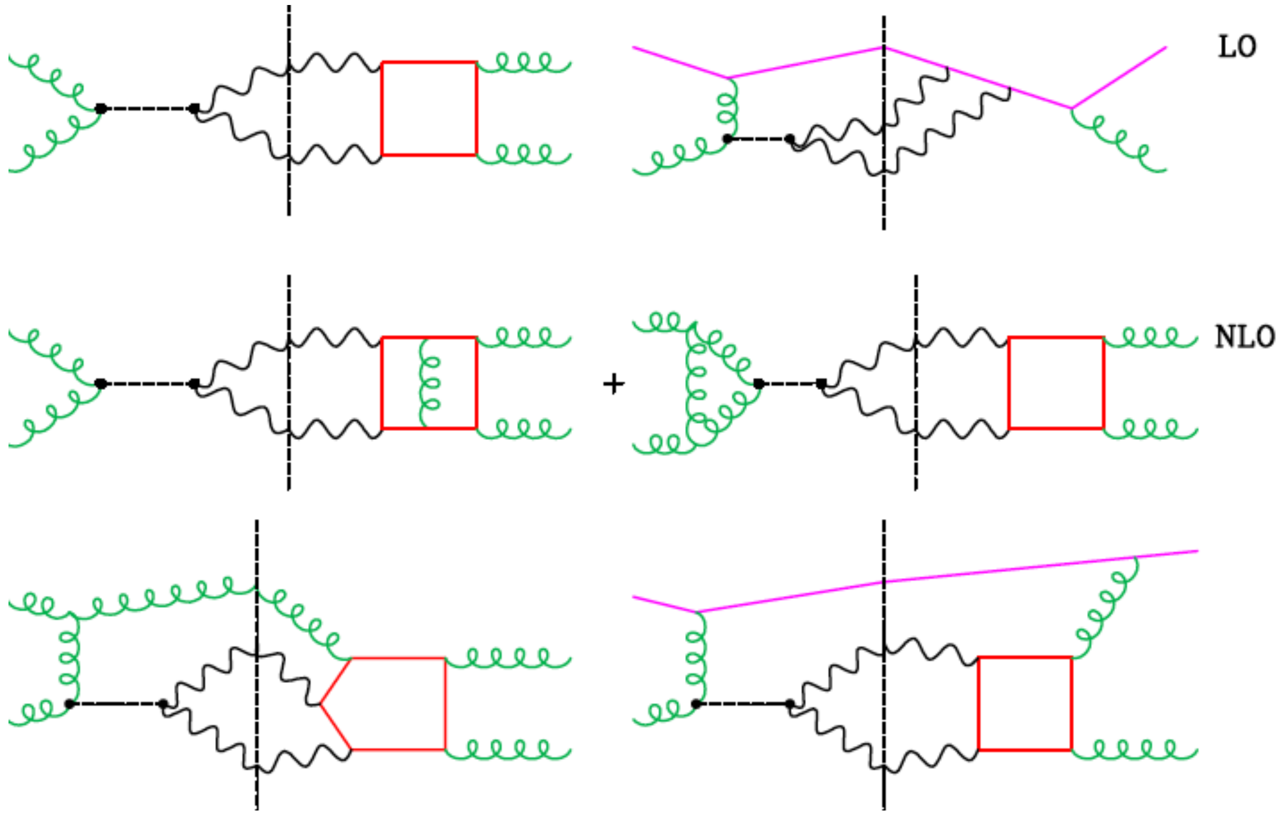
$$-2m_H\Gamma_H\frac{Im(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{cont})}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}$$

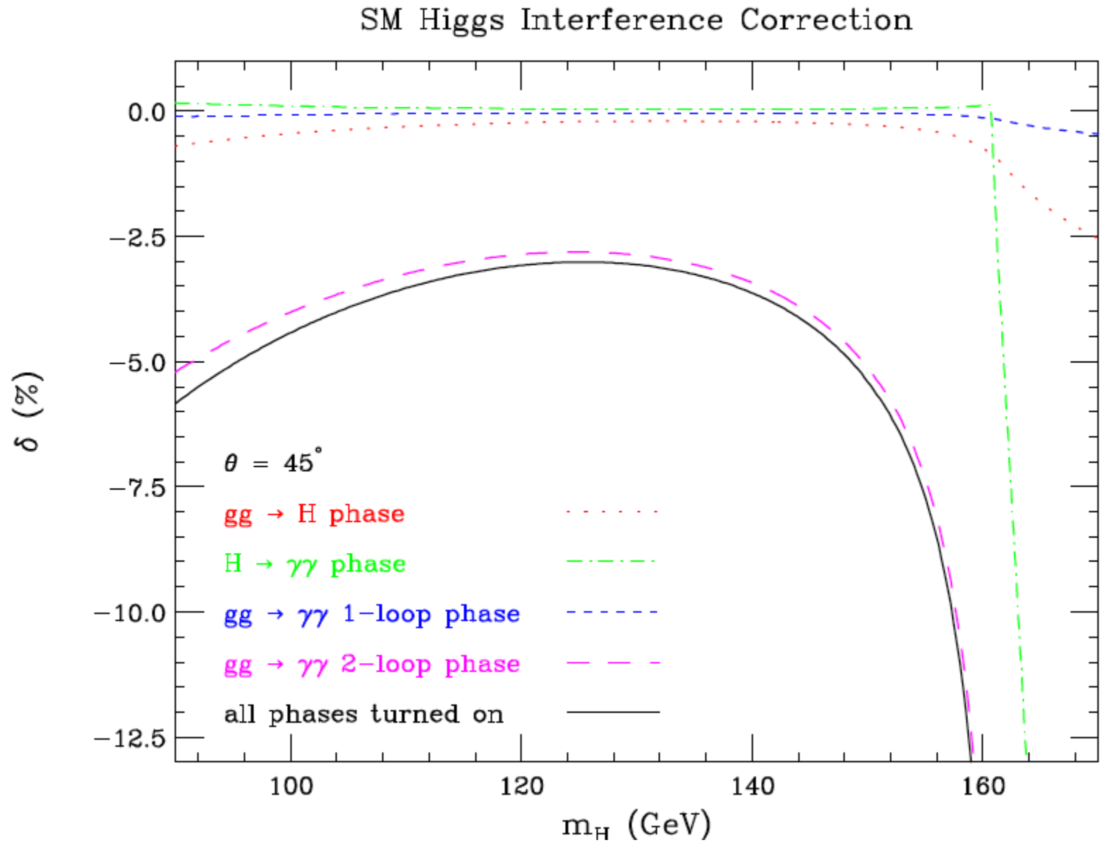
- changes peak height

- Experimental resolution averages over line-shape.

Interference effects in γγ (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%.

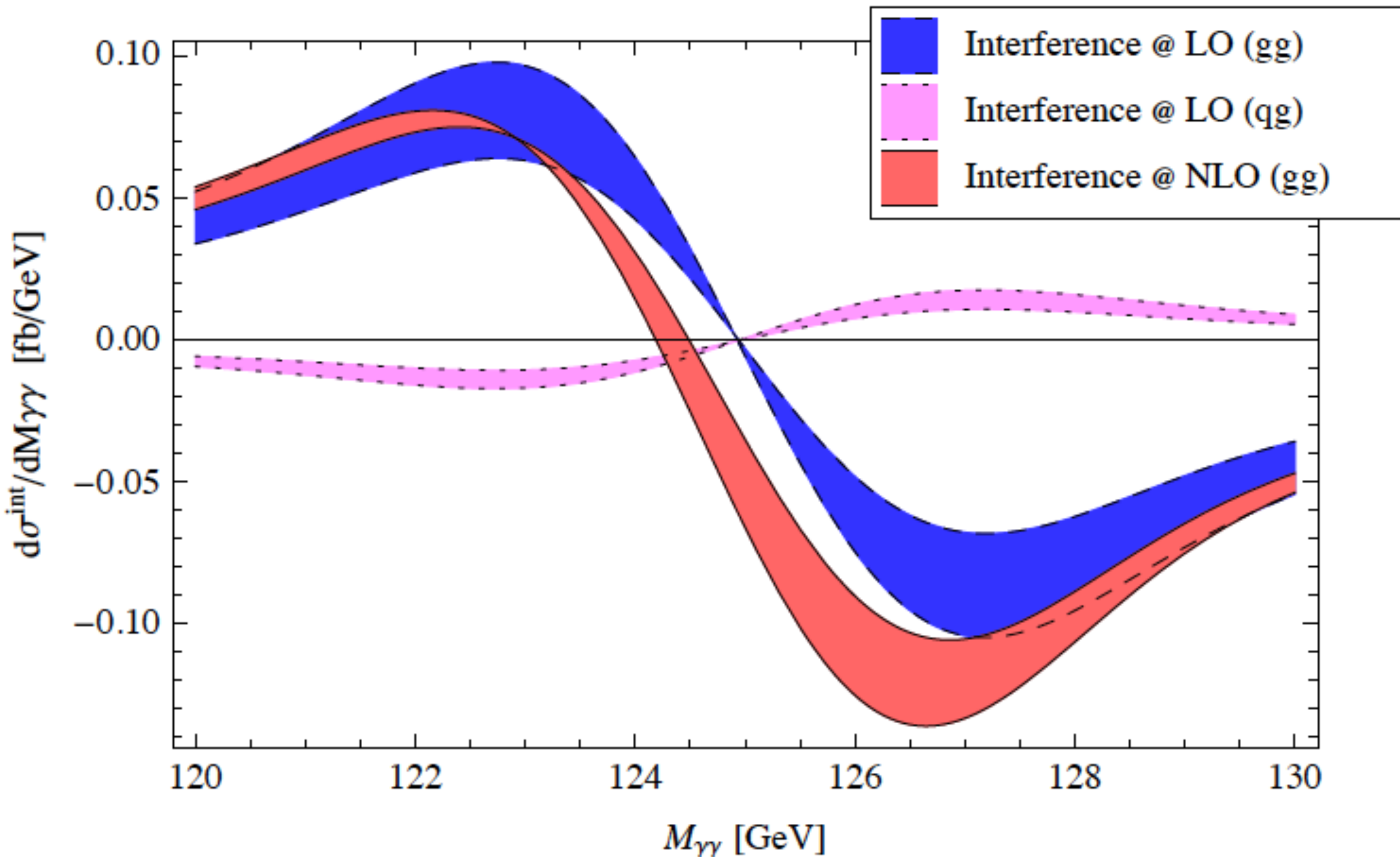




Interference effects in γγ (real part)

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 $200\Gamma_{SM}$

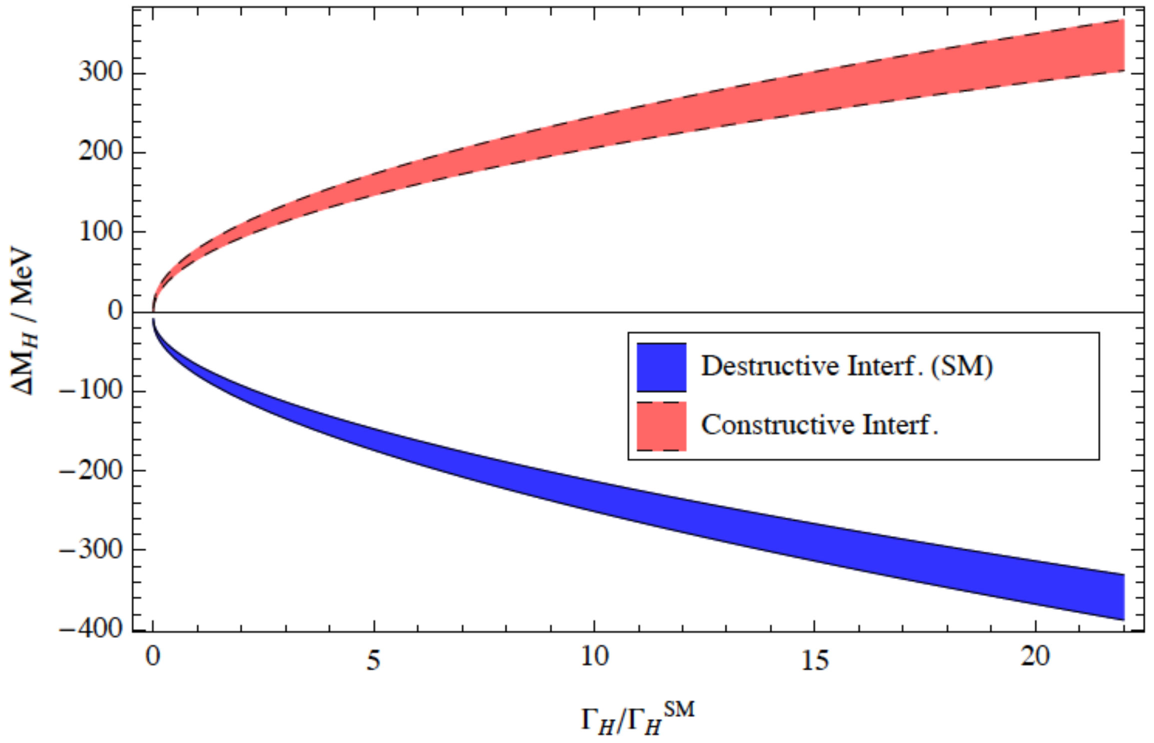
- ATLAS: $m_H^{\gamma\gamma}-m_H^{4l}=+1.47\pm0.72$GeV

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 Δm_H~100MeV, leading to a bound of $15\Gamma_{SM}$ at 95%cl.

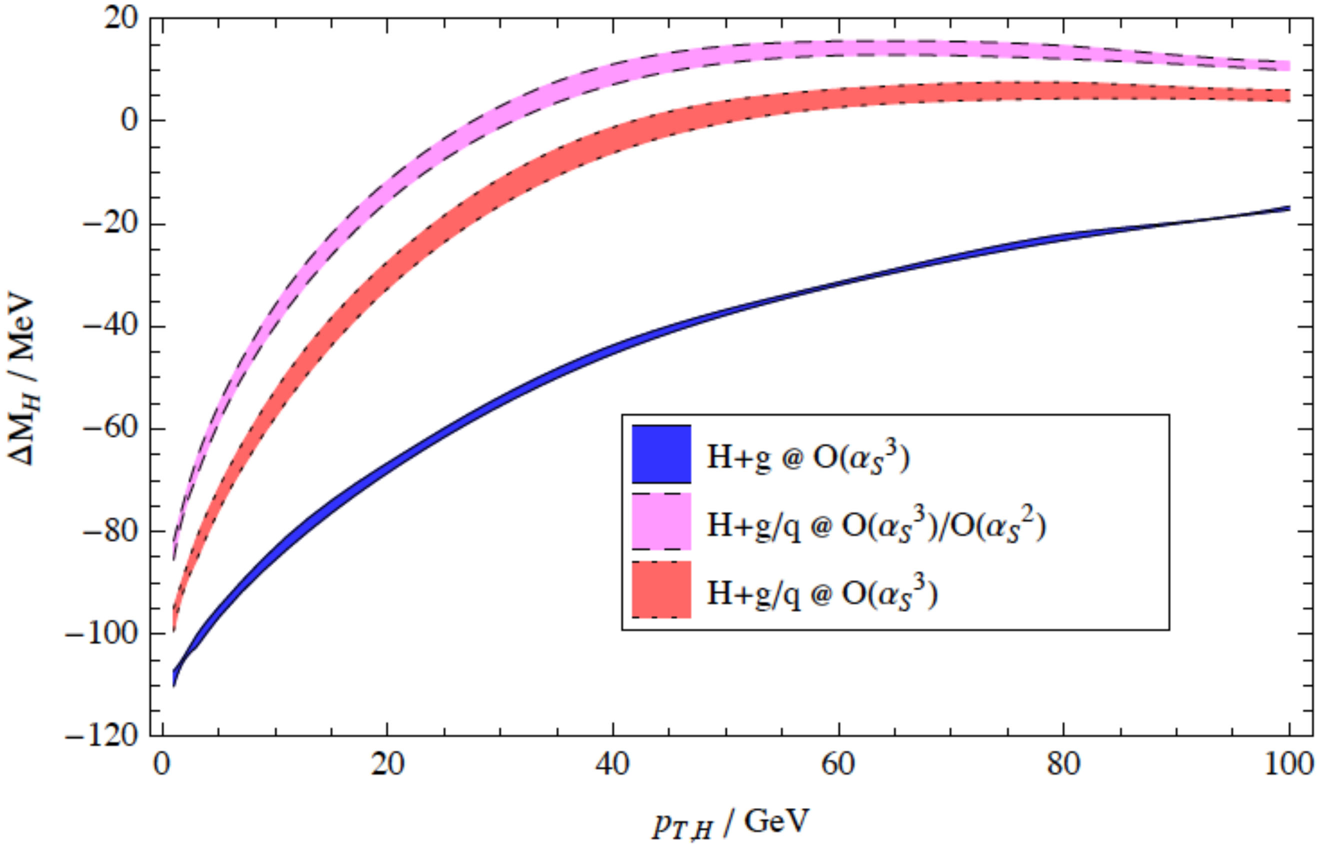


Dixon-Li 1305.3854

Reference masses

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

Martin 1303.3342, Dixon-Li 1305.3854



- γγ mass in vector boson fusion

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

Narrow width approximation for Higgs production

- In the limit $\Gamma/M_h \to 0$ 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

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

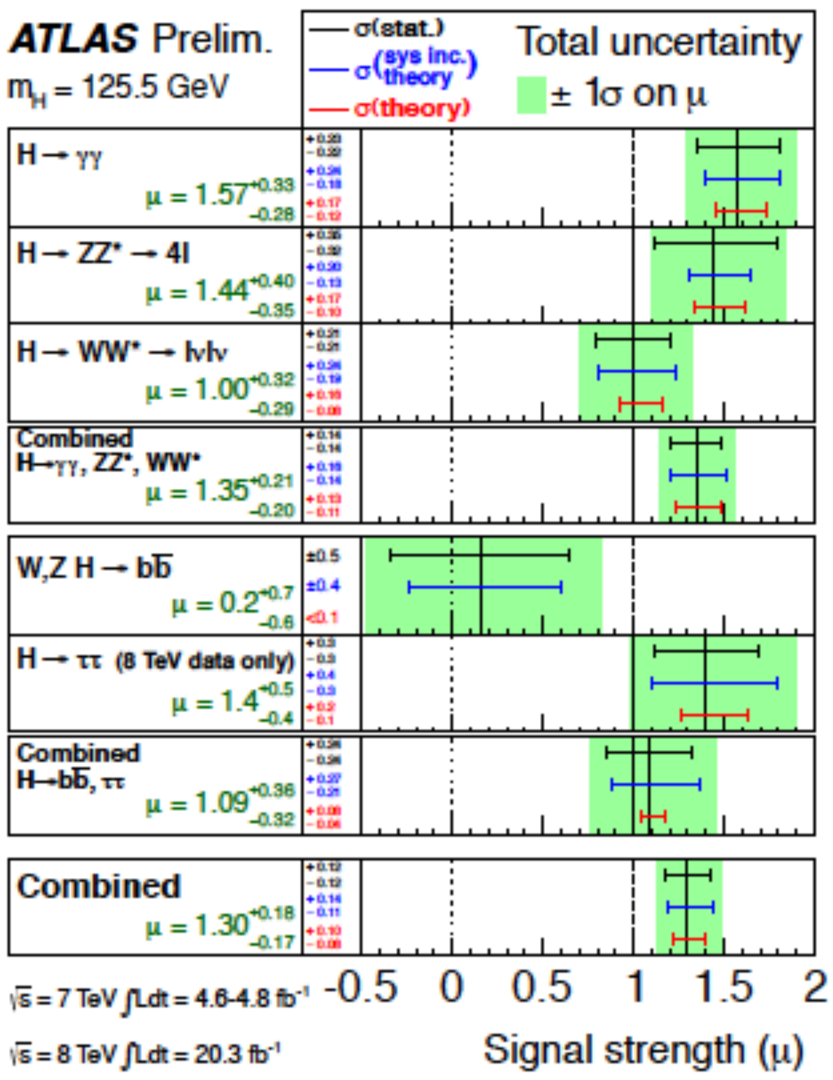
- Measurements on the Higgs peak, are only sensitive to the ratio, $\dfrac{g_i^2 g_f^2}{\Gamma_h}$

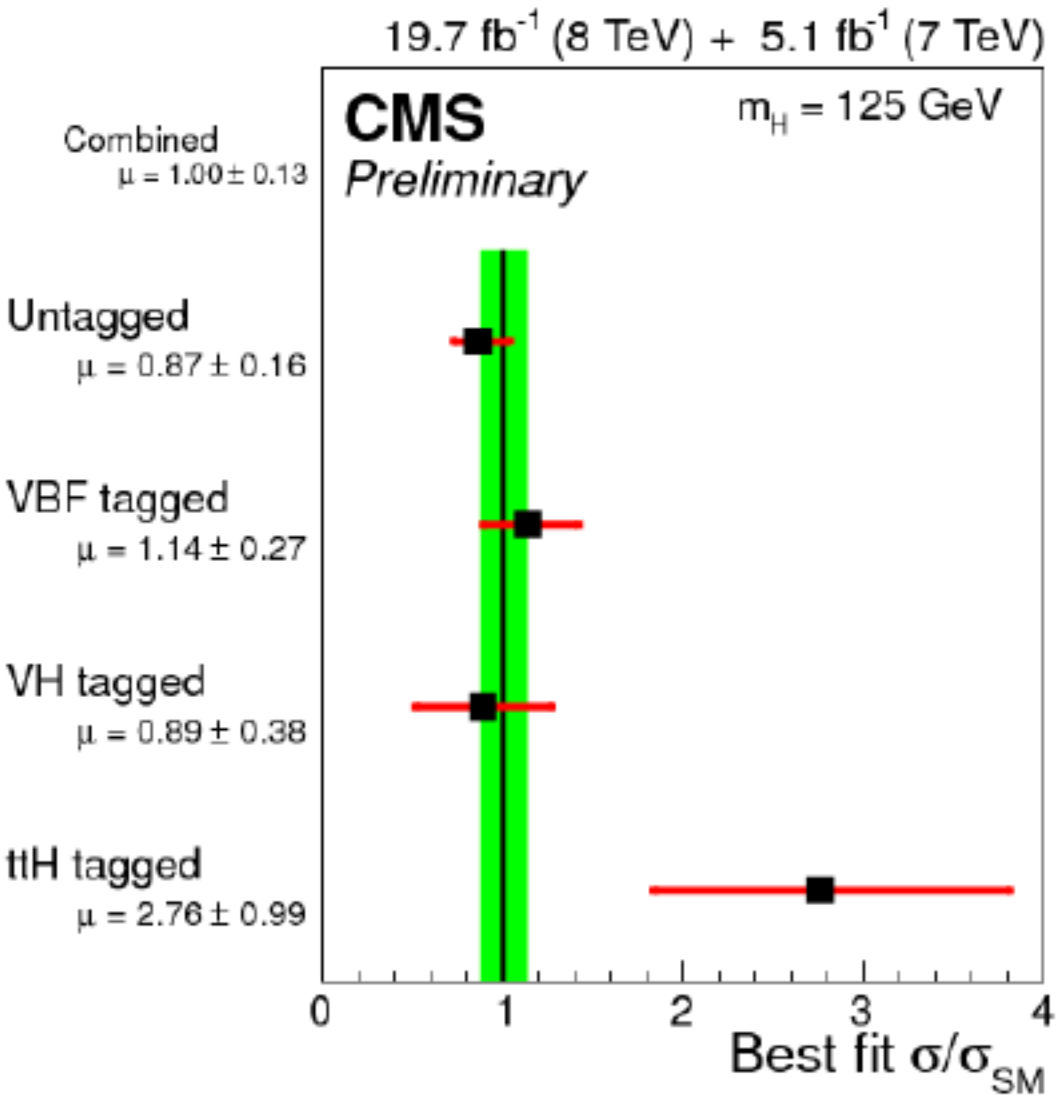
- Performing the rescaling by ξ leaves the measurement unchanged.

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

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.





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

$$\begin{aligned} p + p \to H \;\to\; & ZZ \\ & \;\big|\;\; \hookrightarrow \mu^- + \mu^+ \\ & \hookrightarrow e^- + e^+ \,. \end{aligned}$$

$$\begin{aligned} p + p \;\to\; & Z/\gamma^* + Z/\gamma^* \\ & \big| \qquad\quad \hookrightarrow \mu^- + \mu^+ \\ & \hookrightarrow e^- + e^+ \end{aligned}$$

- Consider the contributing Feynman diagrams.

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

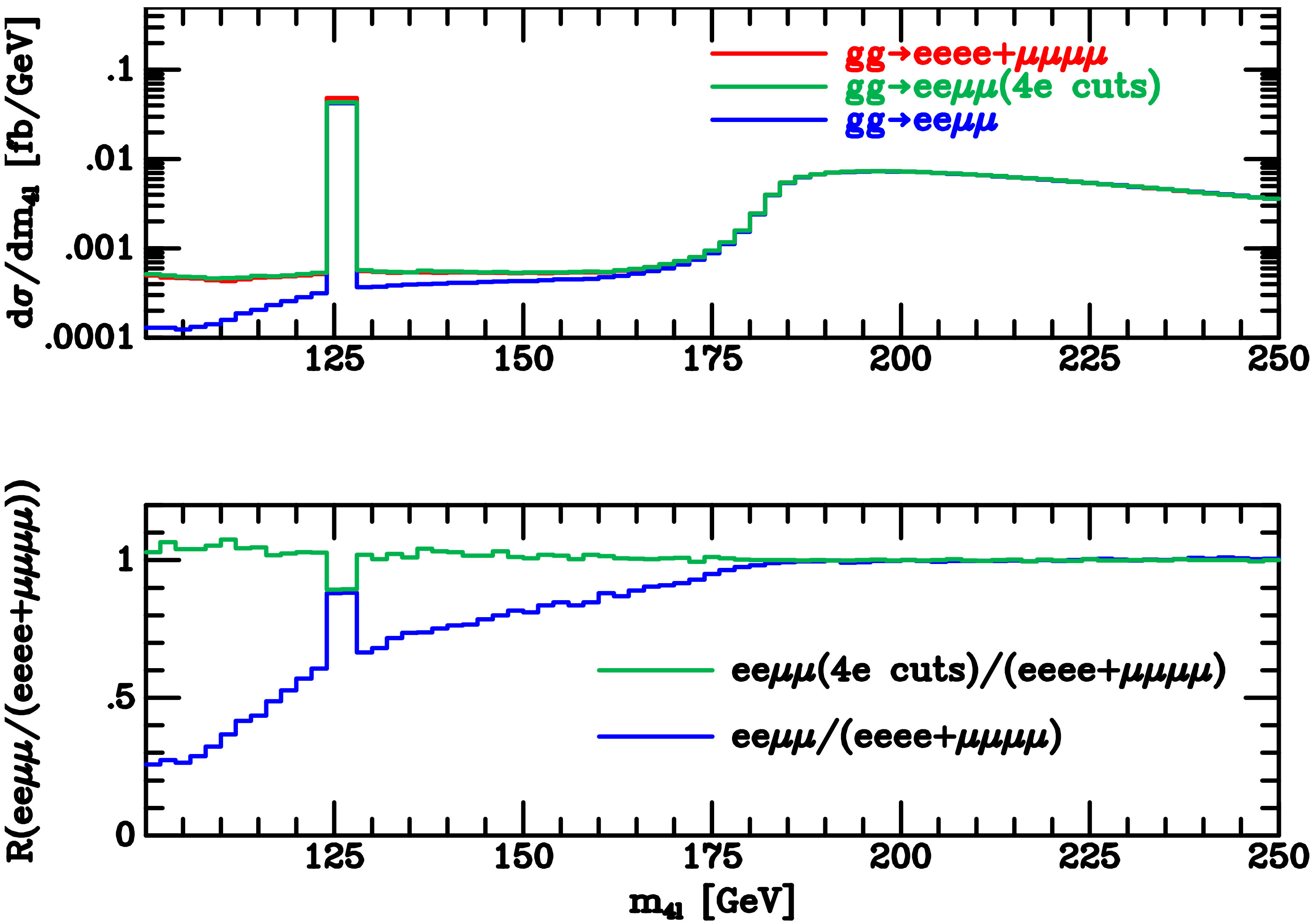
Interference effects in gg processes

- 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

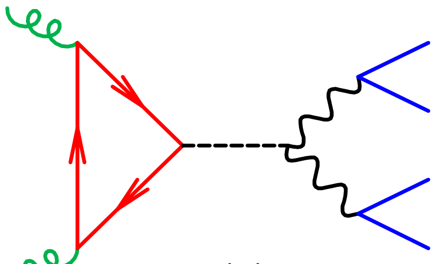


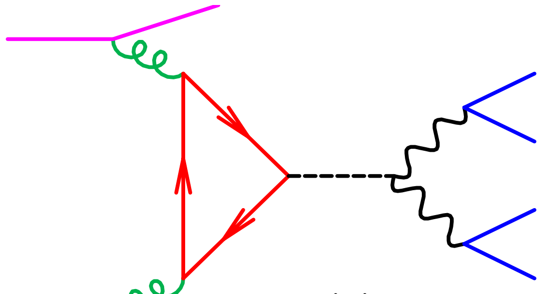
pp→$e^-e^+\mu^-\mu^+$ in the standard model

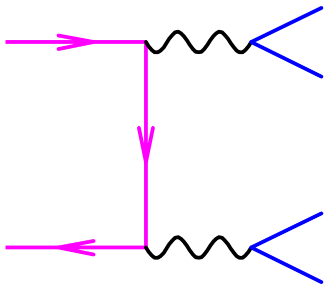
- Mishmash of orders in perturbation theory

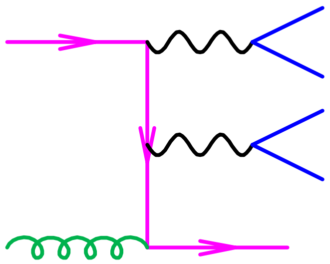
$(a): g(-p_1)+g(-p_2)\to H\to e^-(p_3)+e^+(p_4)+\mu^-(p_5)+\mu^+(p_6)$	$O(g_s^2e^4)$
$(b): q(-p_1)+g(-p_2)\to H\to e^-(p_3)+e^+(p_4)+\mu^-(p_5)+\mu^+(p_6)+q(p_7)$	$O(g_s^3e^4)$
$(c): q(-p_1)+\bar{q}(-p_2)\to e^-(p_3)+e^+(p_4)+\mu^-(p_5)+\mu^+(p_6)$	$O(e^4)$
$(d): q(-p_1)+g(-p_2)\to e^-(p_3)+e^+(p_4)+\mu^-(p_5)+\mu^+(p_6)+q(p_7)$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

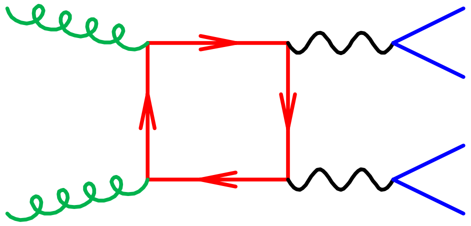
- Representative diagrams are:-
- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e) see later.


(a)


(b)


(c)

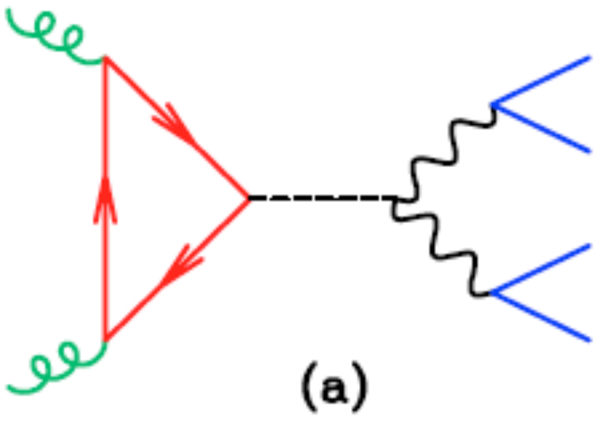

(d)

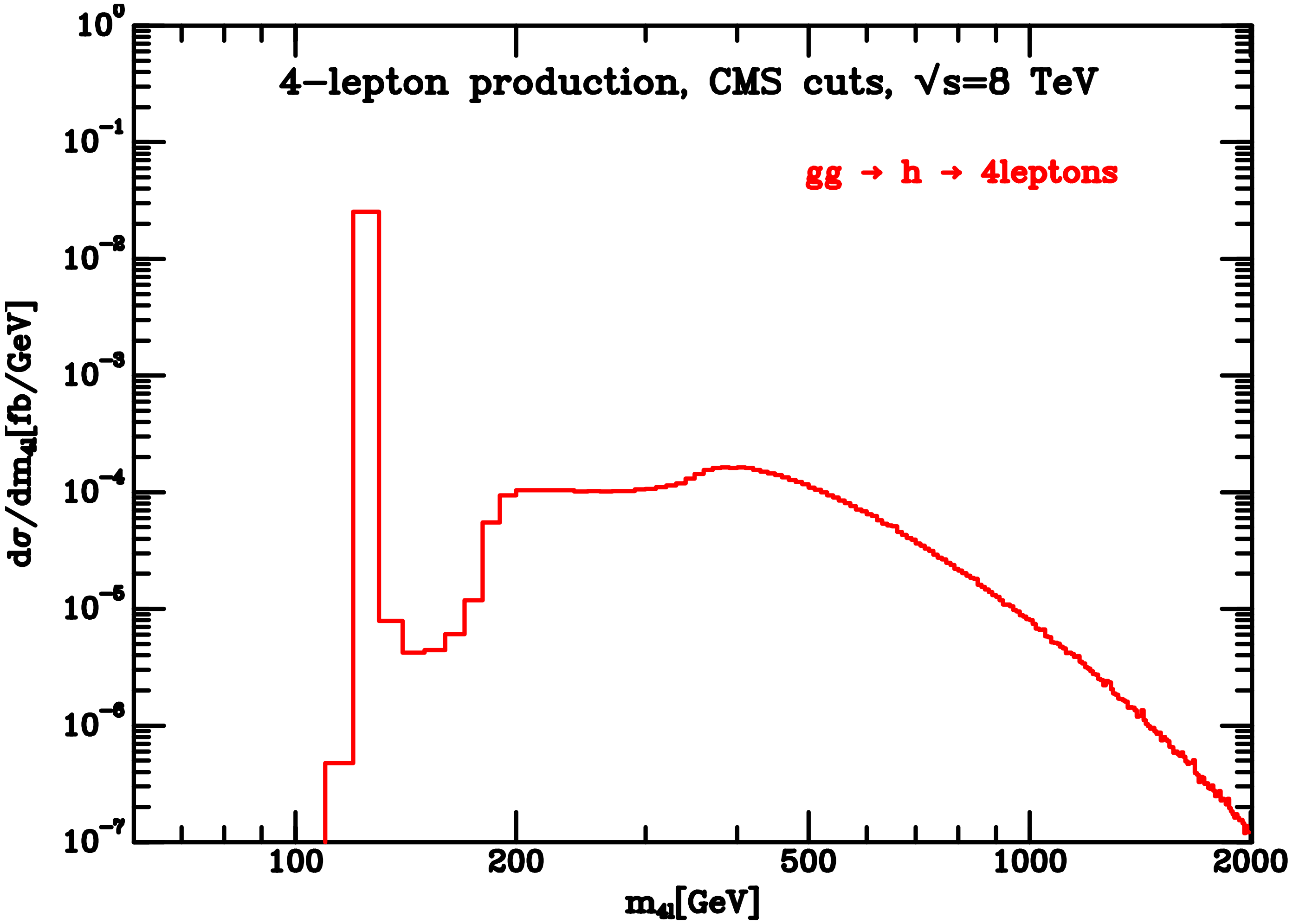

(e)

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 15% 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→WW.



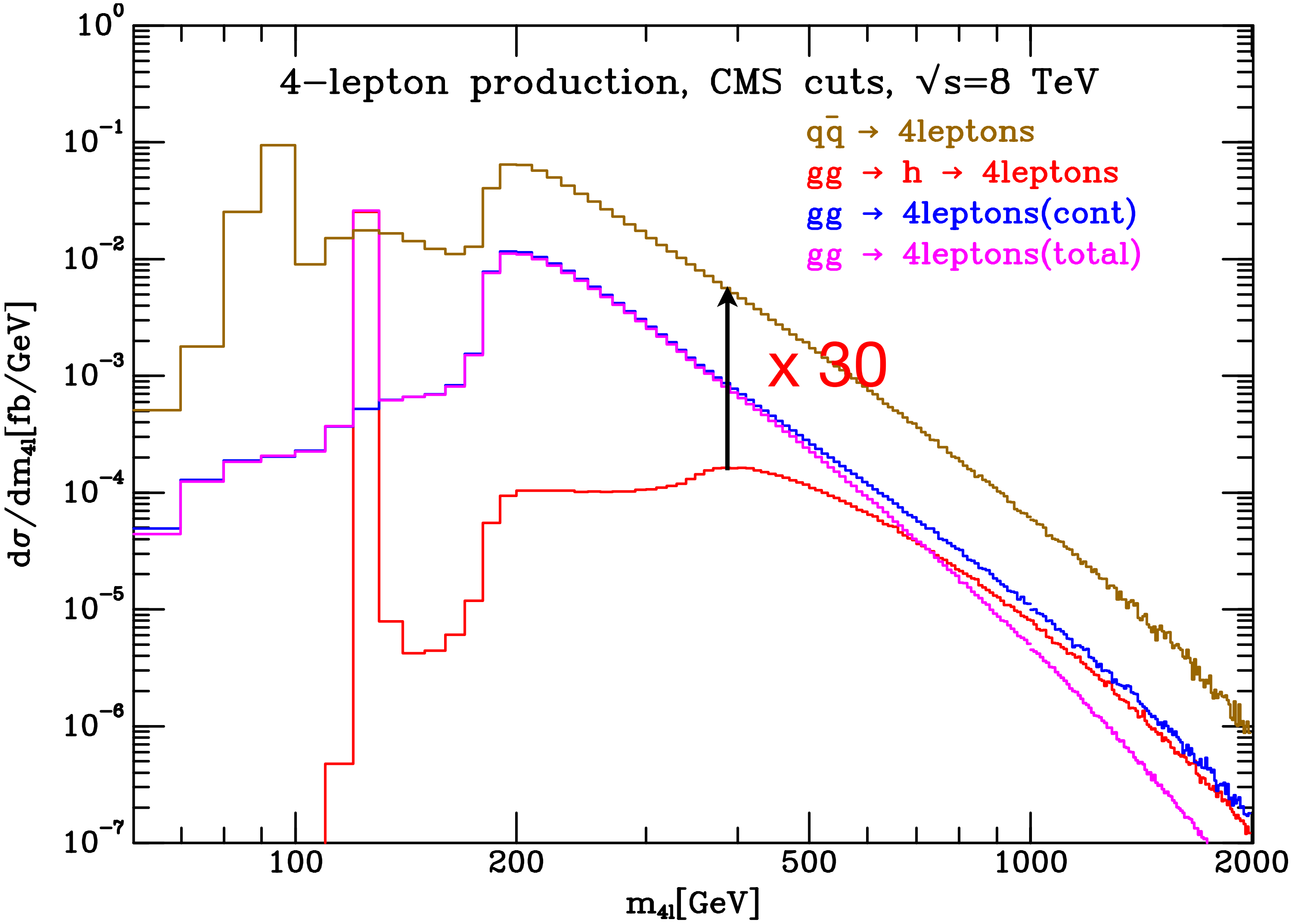


The big picture @ 8TeV

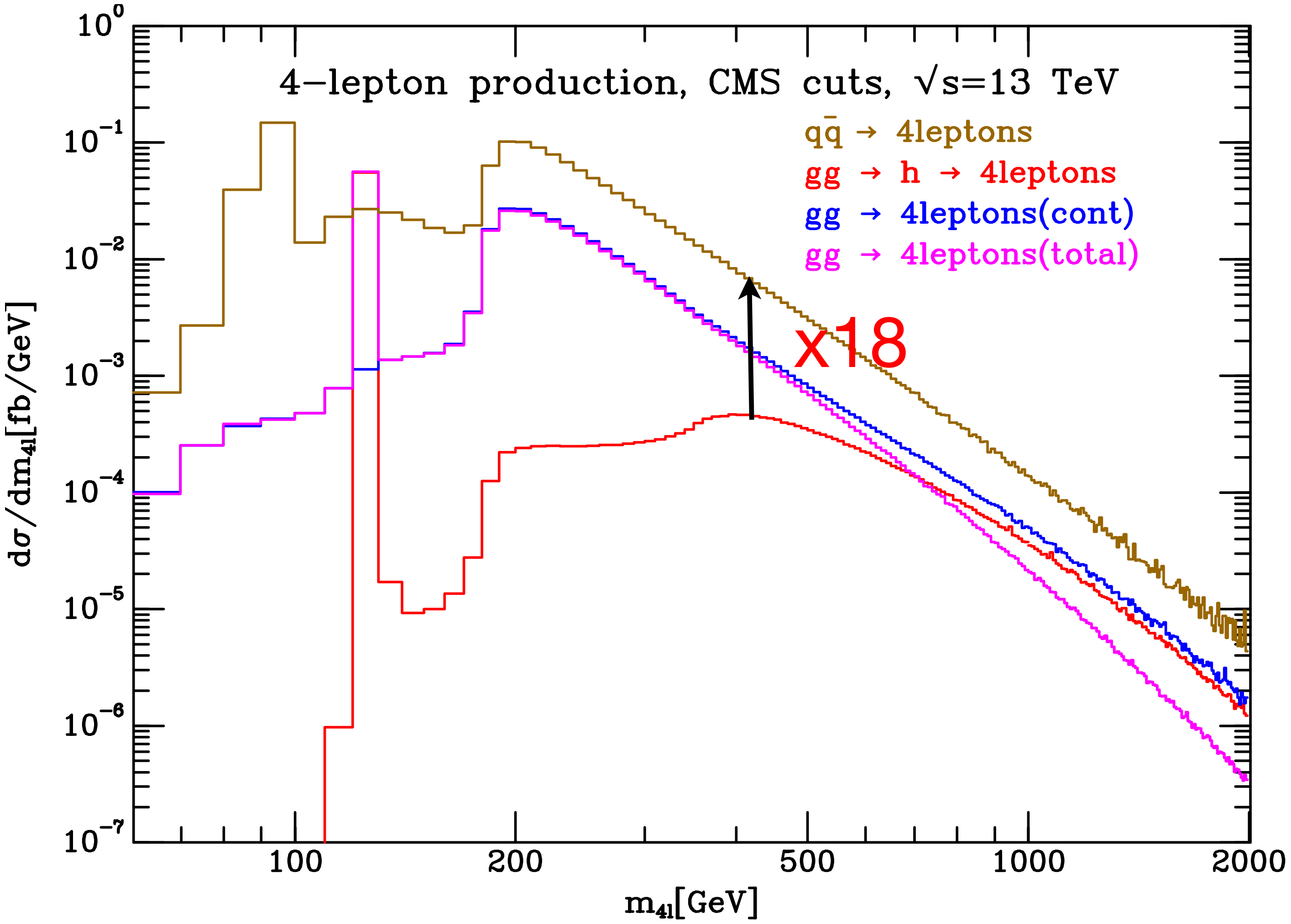
- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width, Γ_H , challenging to see enhancement/deficit due to Higgs channel.

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

CMS cuts
CMS PAS HIG-13-002



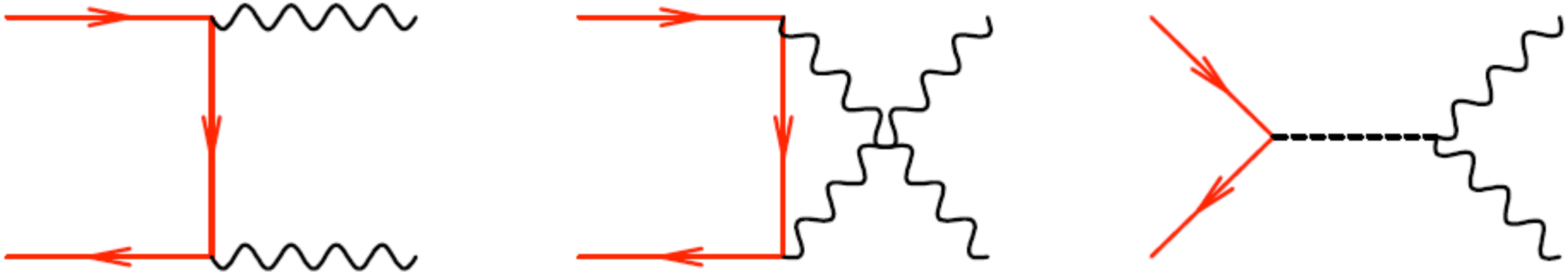
The big picture @ 13 TeV



- σ_{qqb} (m_{4l}=400)/σ^{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.

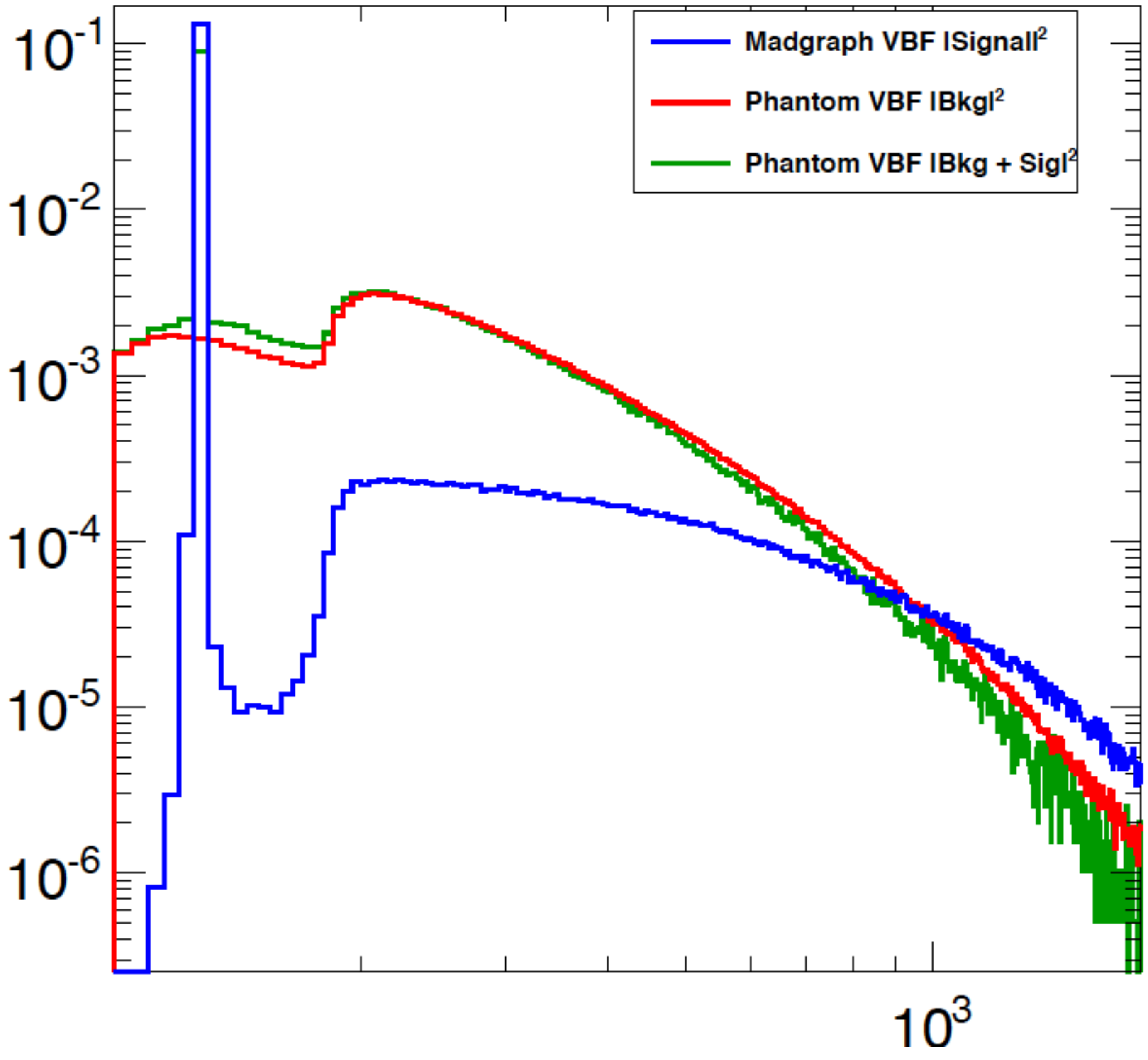


$a_2E^2+(b_1+a_1)m_tE$ $\quad$ $-a_2E^2+(c_1-a_1)m_tE$ $\quad$ $-(b_1+c_1)\,m_tE$

- 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

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

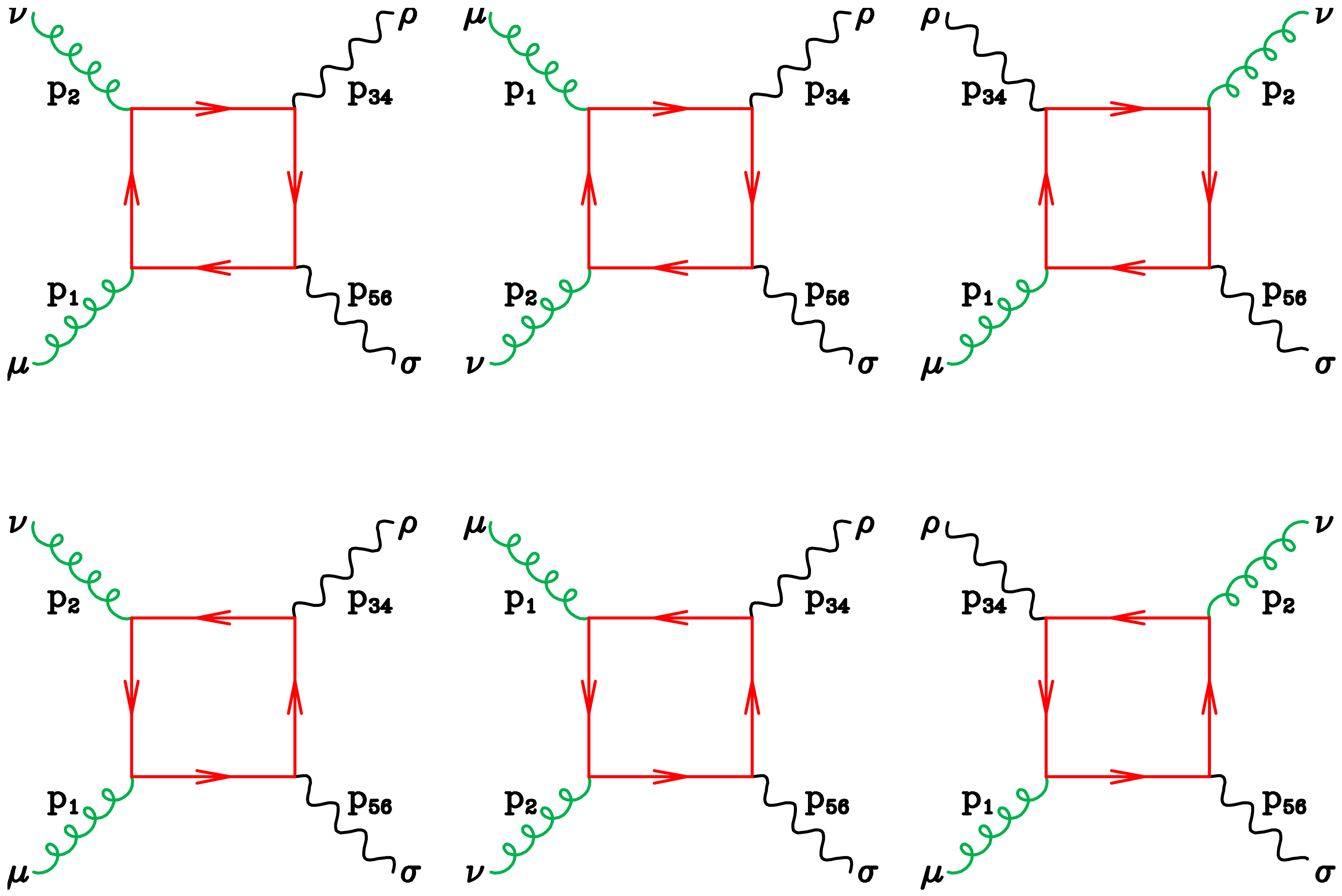
- Ratio depends linearly on the Higgs boson width.

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.

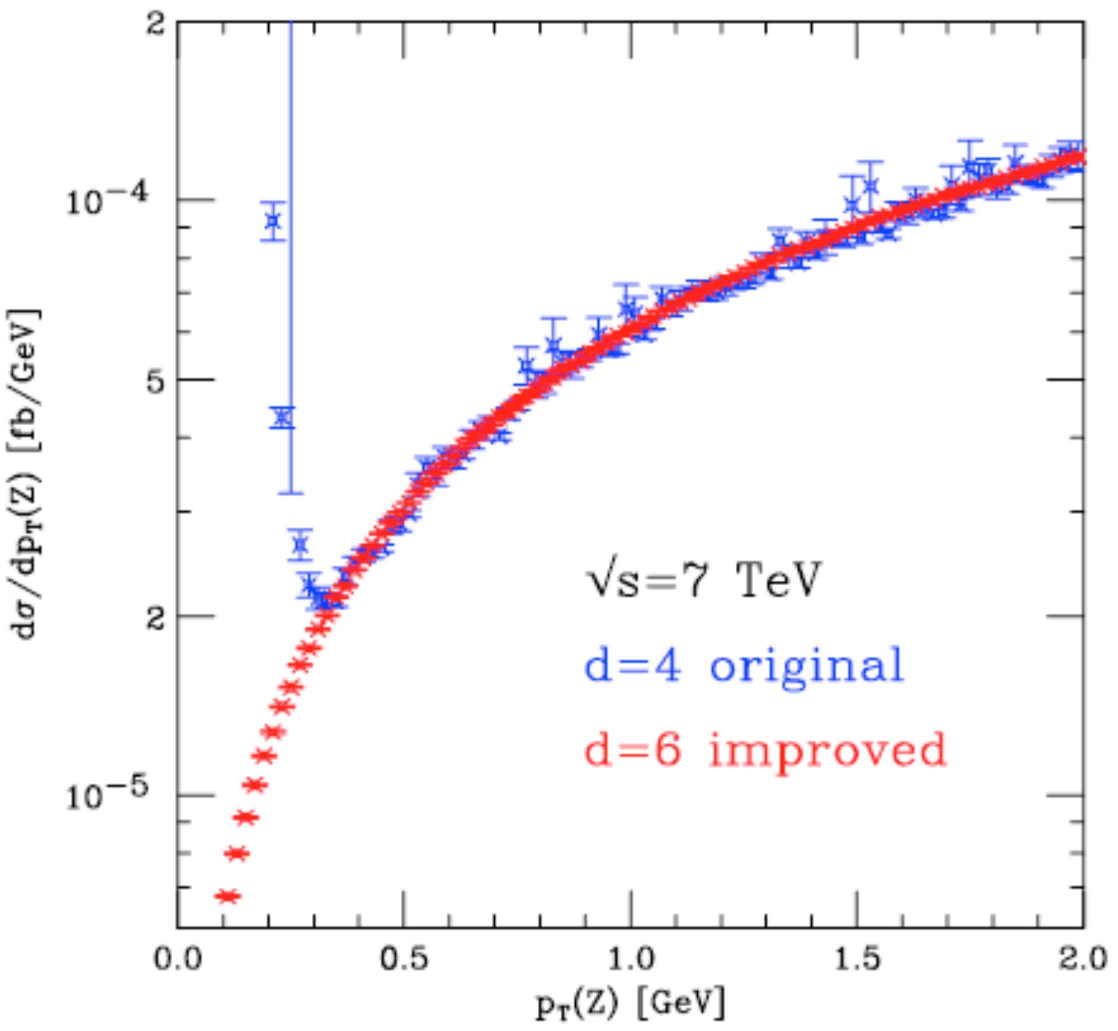
Campbell, Ellis, Williams, 1311.3589

$P_T=0$

- Translating back to Bjorken-Drell notation,

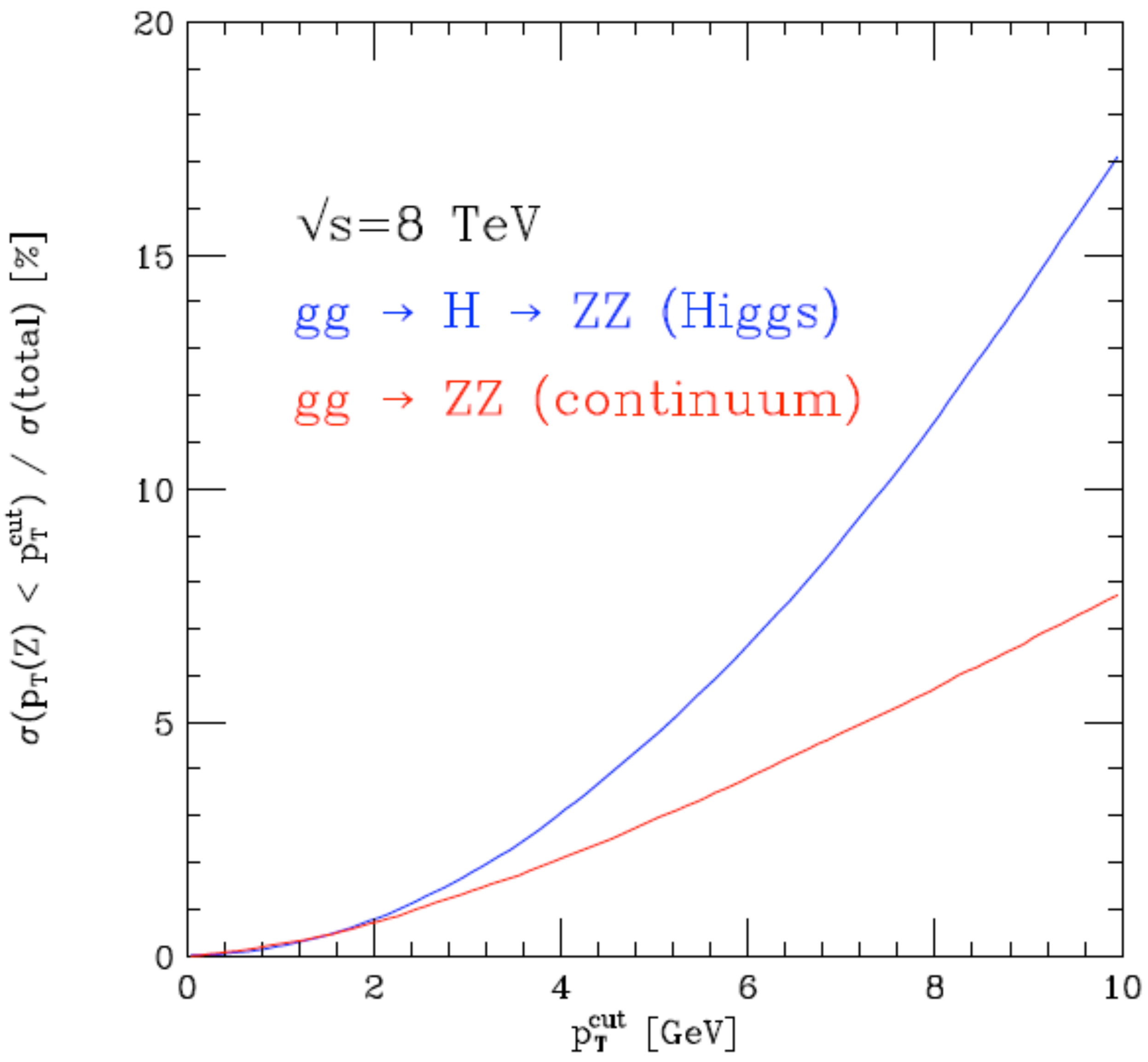
$$\langle 2|(3+4)|1] = \bar{u}_-(p_2)(\not{p}_3+\not{p}_4)u_-(p_1)$$

- 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?

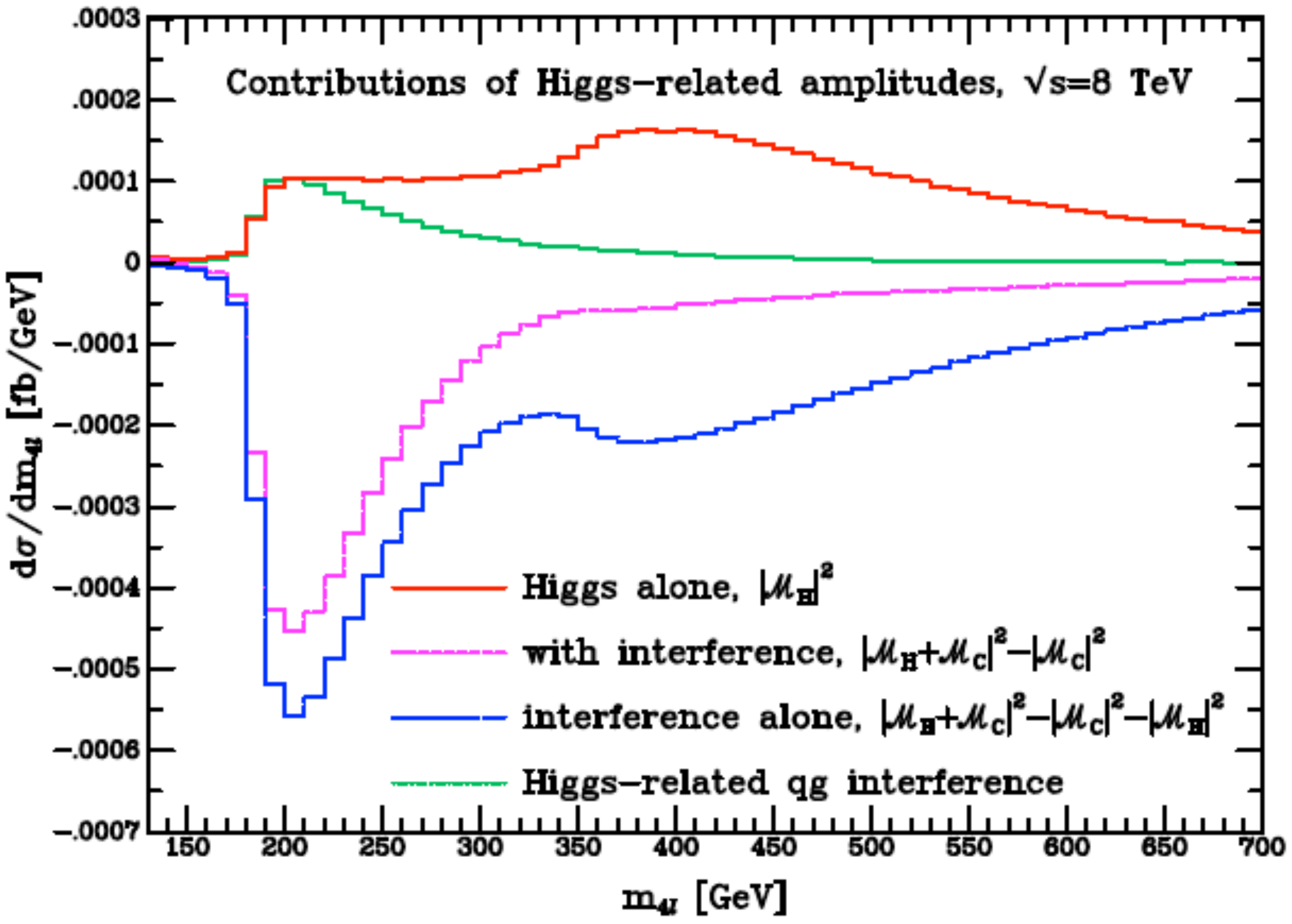
- 8% of the $gg \rightarrow H \rightarrow ZZ^* \rightarrow e^- e^+ \mu^- \mu^+$ cross section, comes from the region where $p_T^Z < 7$GeV.
- We impose a cut of $p_T^Z < 0.1$GeV, (i.e. less than 0.01% of cross section.



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.

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

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

- 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).

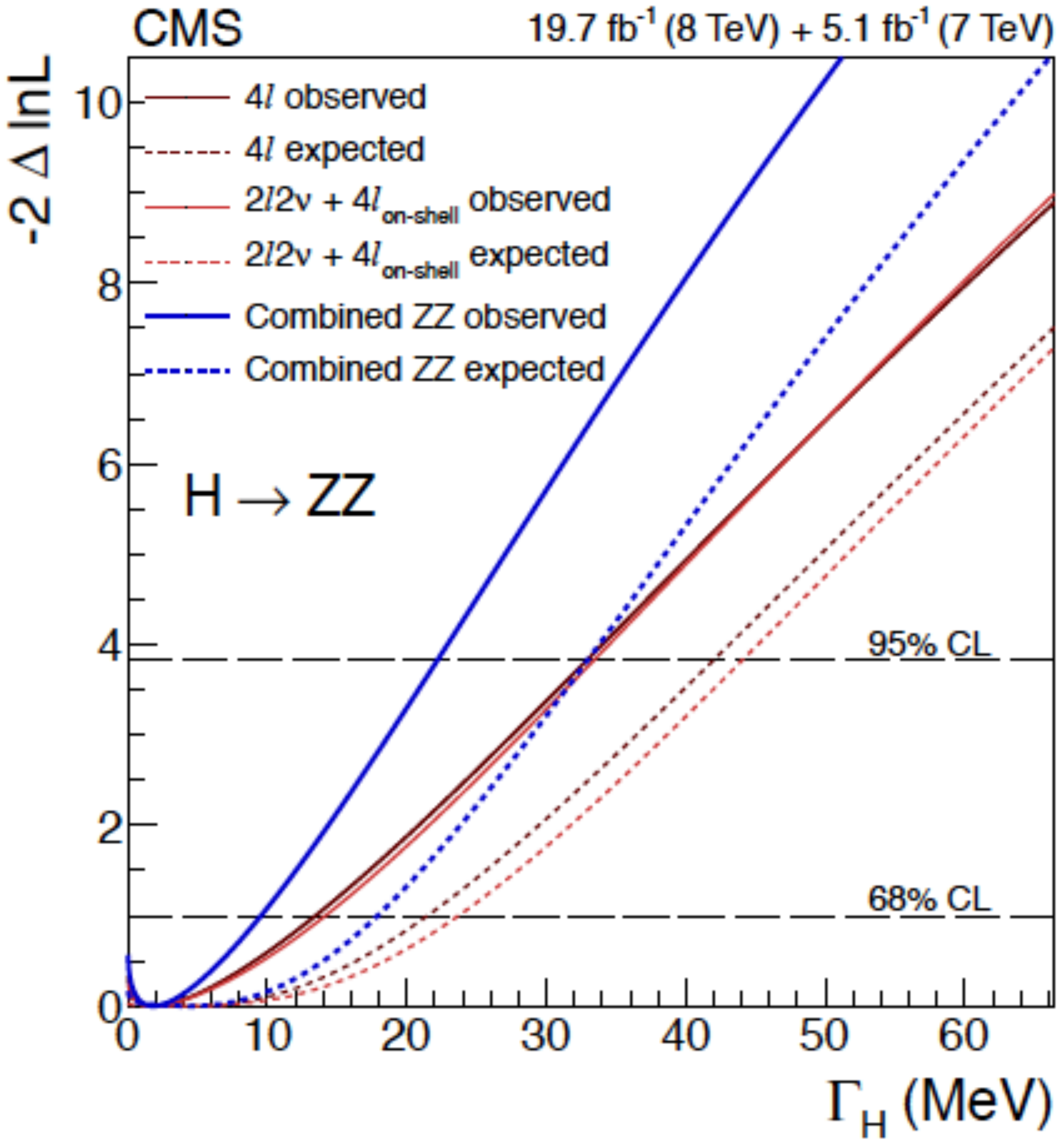
$$N^{4\ell}_{off}(m_{4\ell} > 130 \text{ GeV}) = 2.78 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

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

CMS result

arXiv:1405.3455

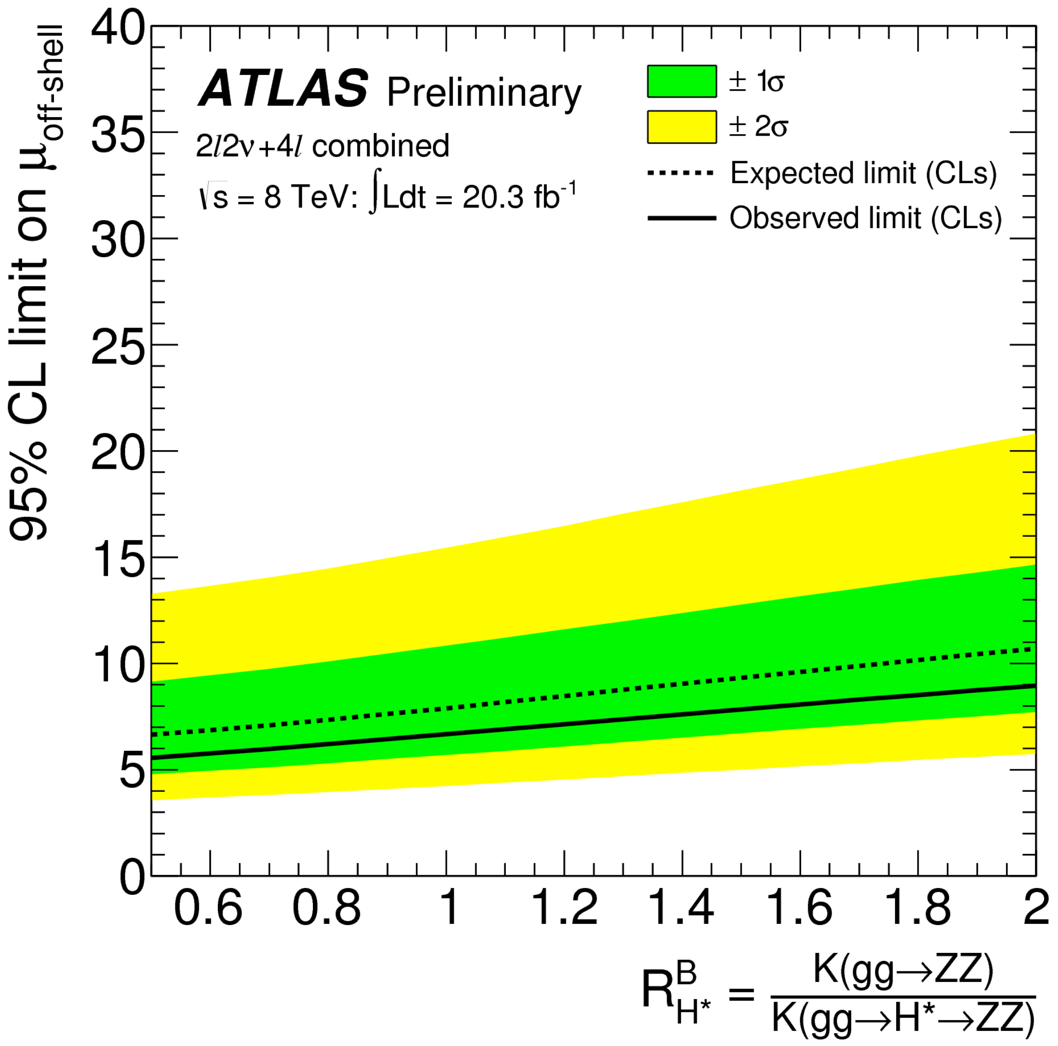
- Γ_H/Γ_H^{SM}=5.4 at 95%cl

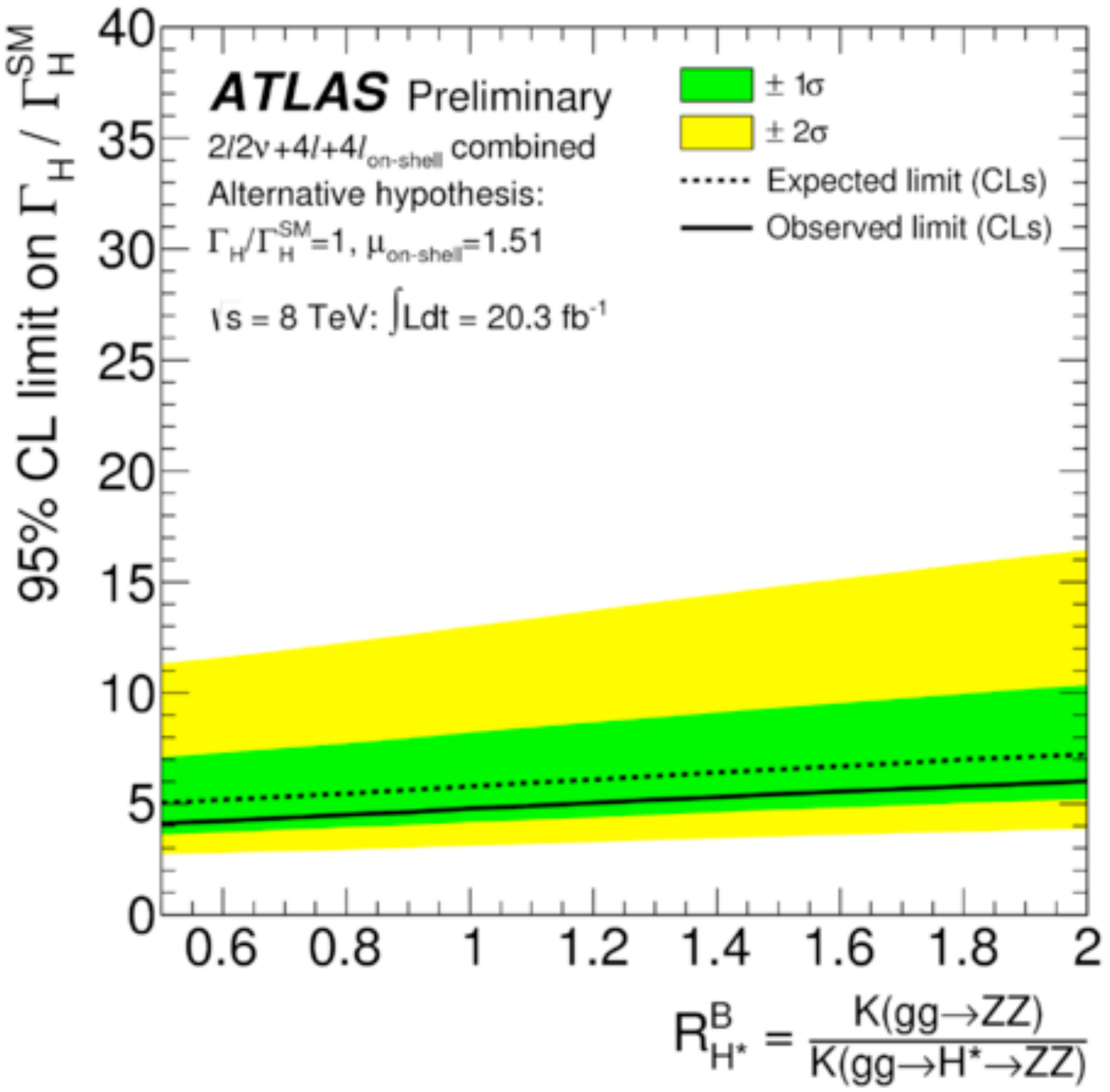


ATLAS result

ATLAS-CONF-2014-042

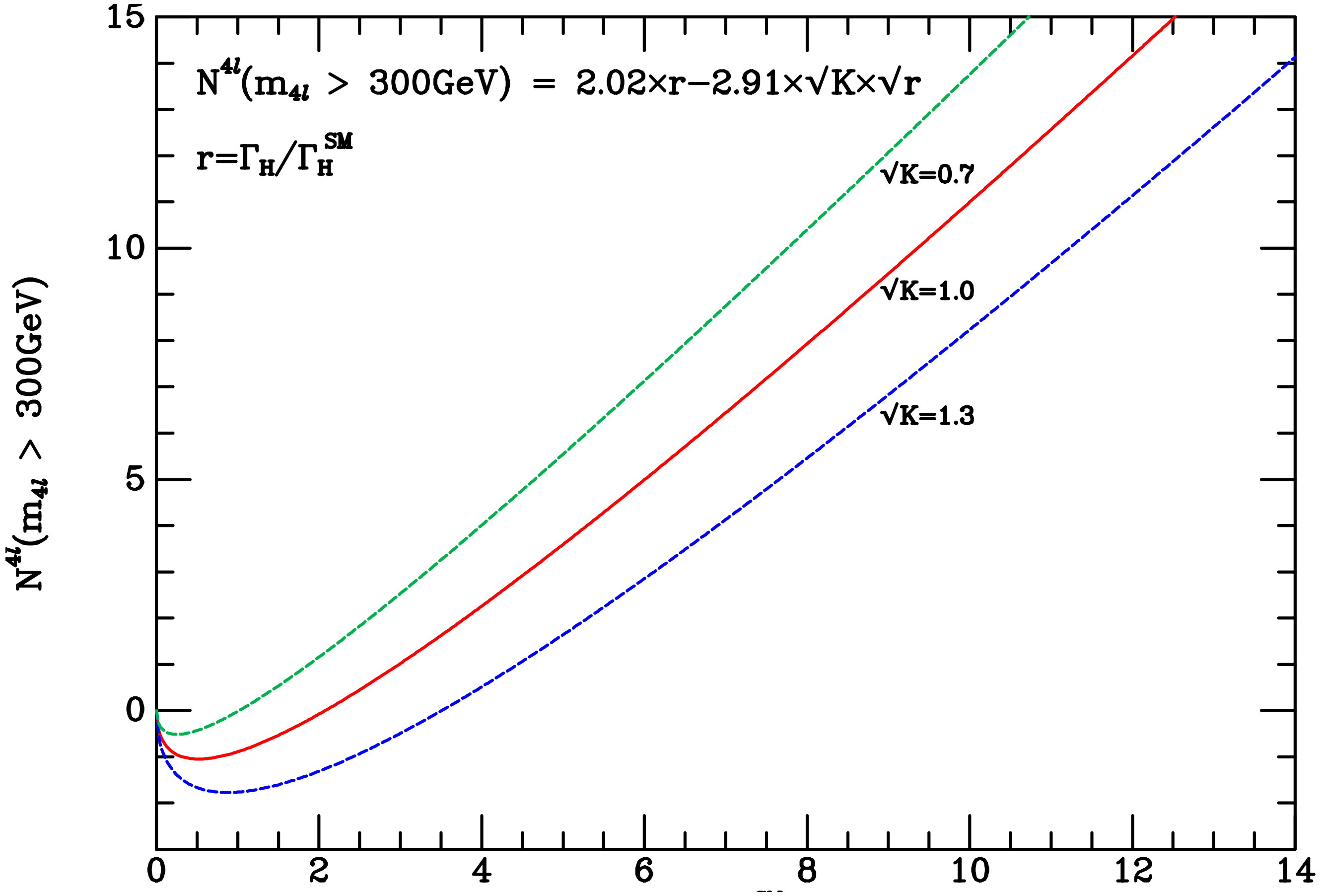
- Result for both off-shell coupling and width as a function of relative K-factor
- Γ_H/Γ_H^{SM}=4.8/7.7 at 95%cl





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

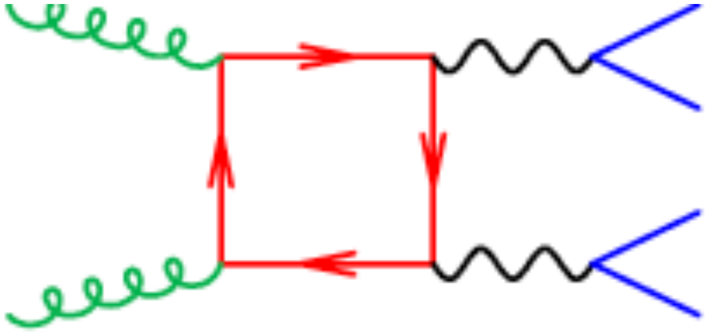


$$\frac{\Gamma_H}{\Gamma_H^{SM}} < \{3.0, 4.2, 5.75\} \text{ for } \sqrt{K} = \{0.7, 1.0, 1.3\}\,.$$

Rationale for assuming K=1?

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

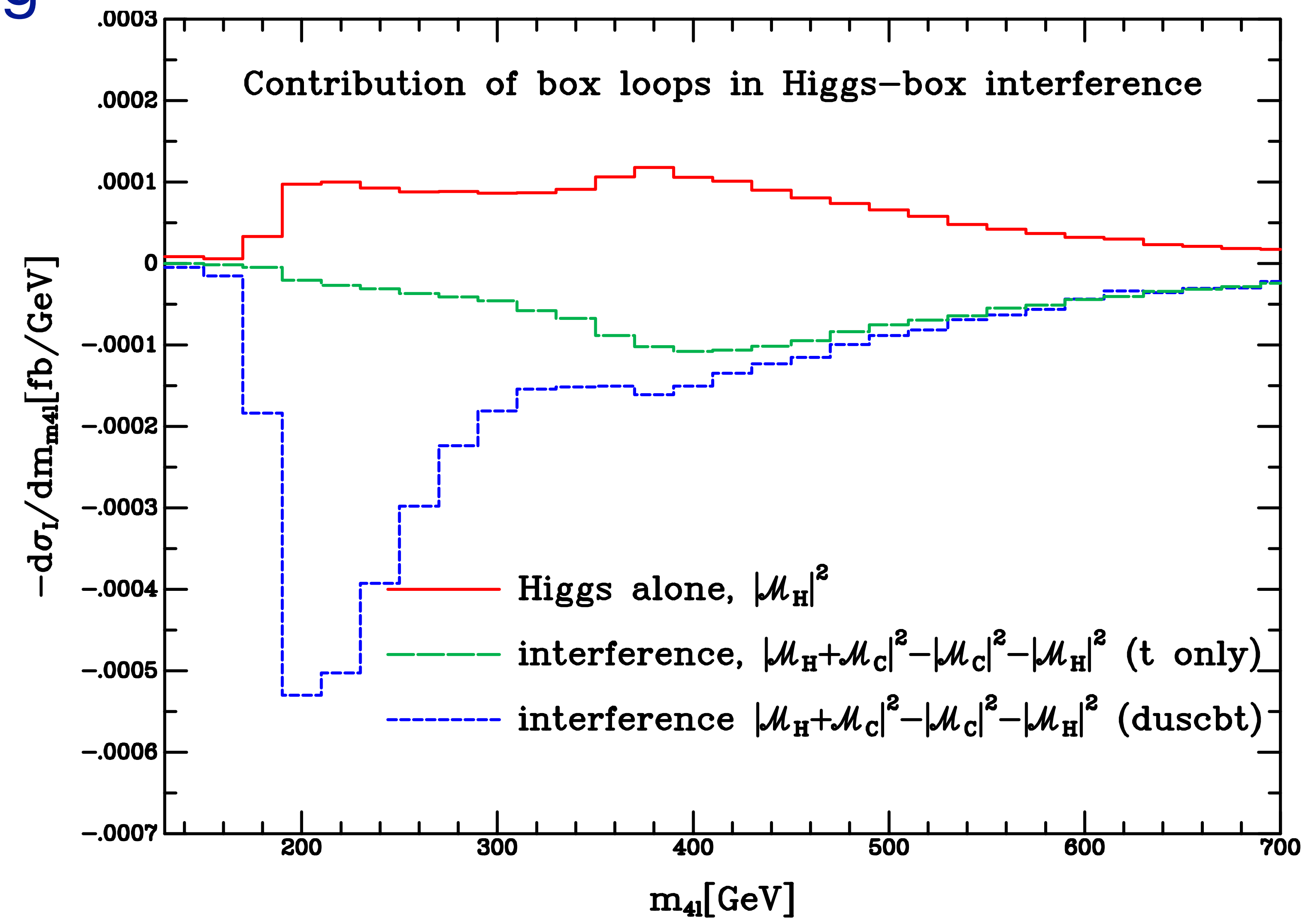
  Bonvini et al, 1304.3053



- 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)

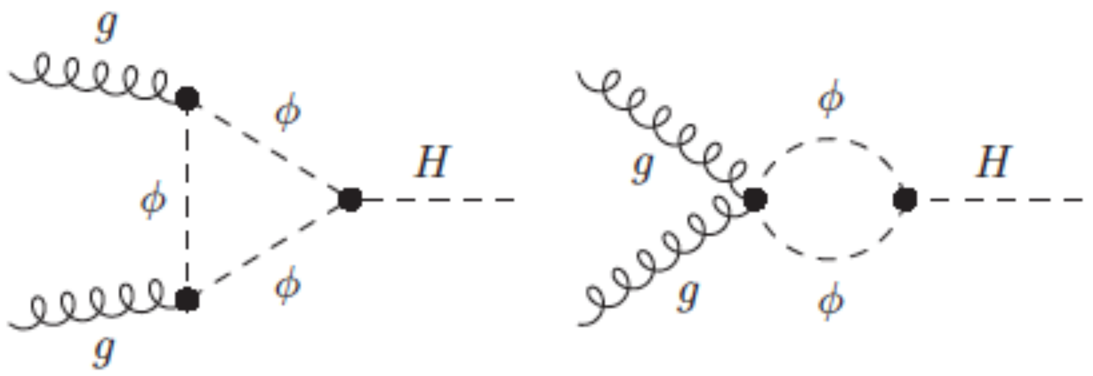
- K factor estimated using soft ideas, applied to production of 600GeV Higgs boson H→WW (Bonvini et al, 1304.3053)

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

- 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).

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 $\mu=1$ 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.

Cacciapaglia et al, 1406.1757
Azatov et al, 1406.6338

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

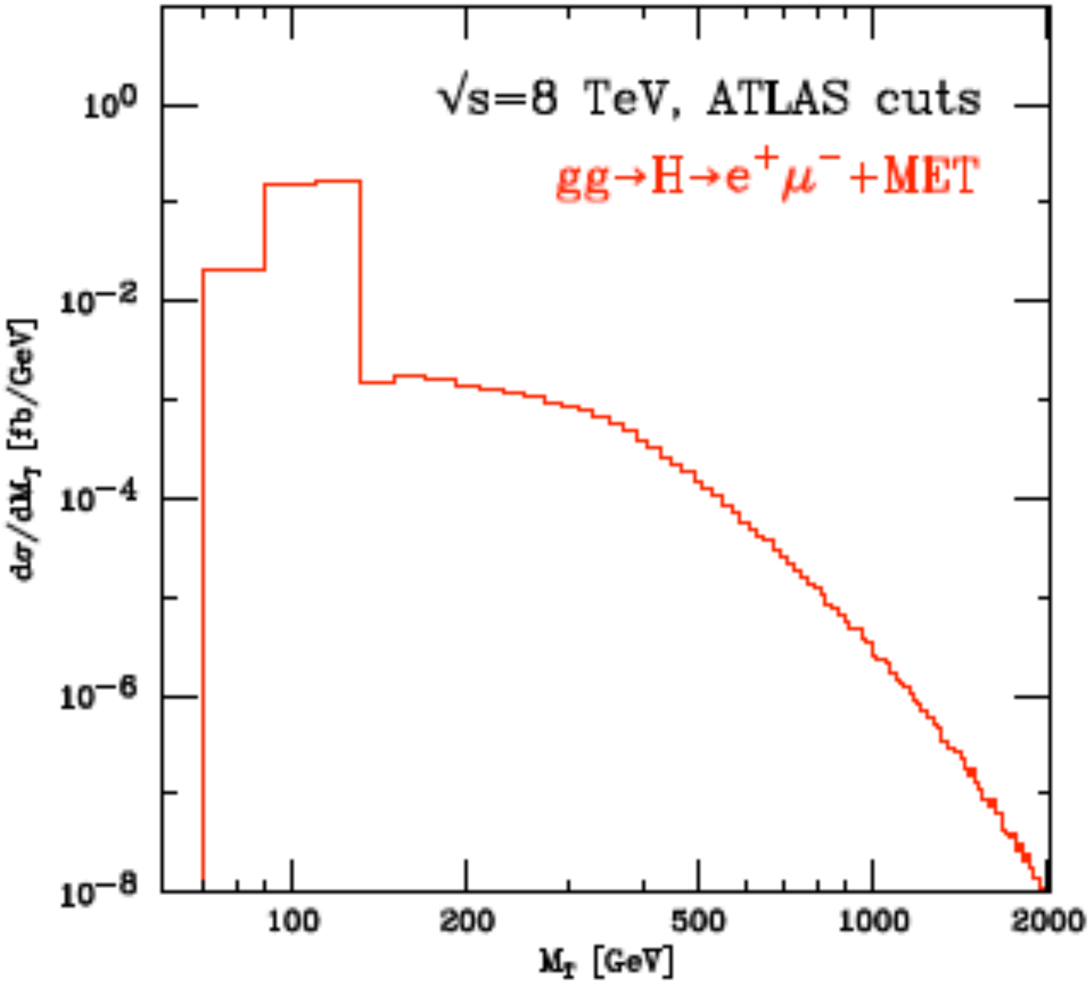
WW

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

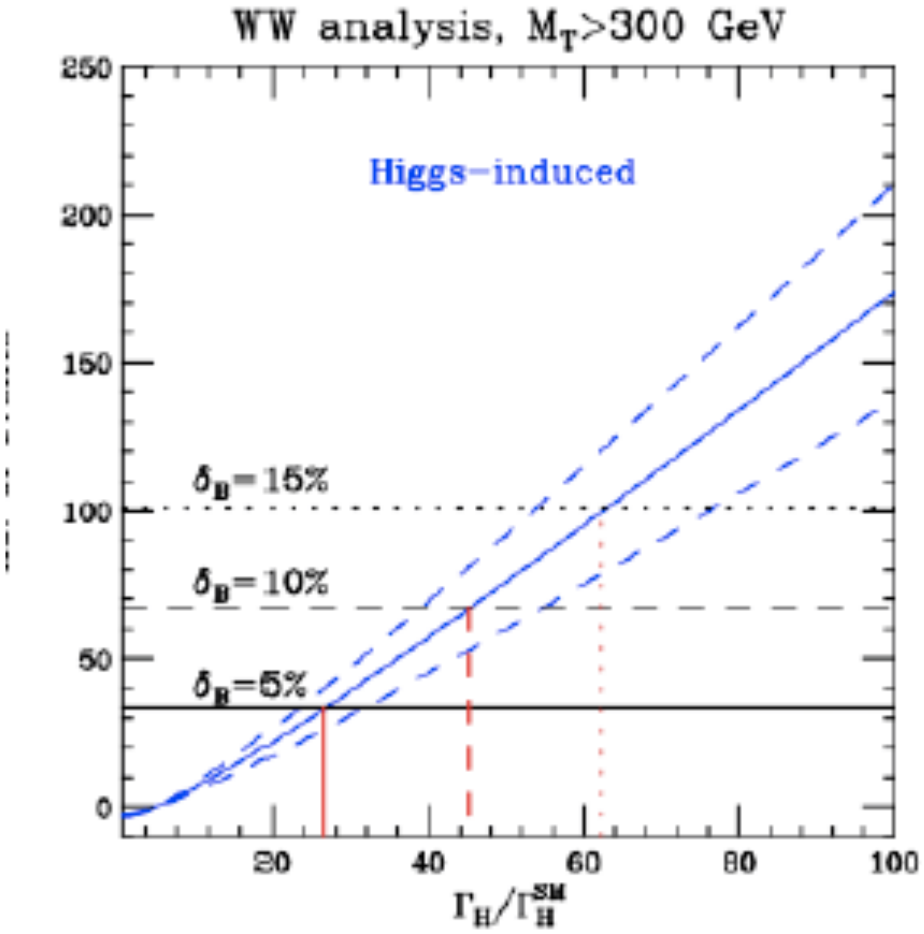
- Advantages
  - Threshold for two real W's much closer than for Z's
  - branching ratio to leptons higher
  - combined, two orders of magnitude more events

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

- 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.

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

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

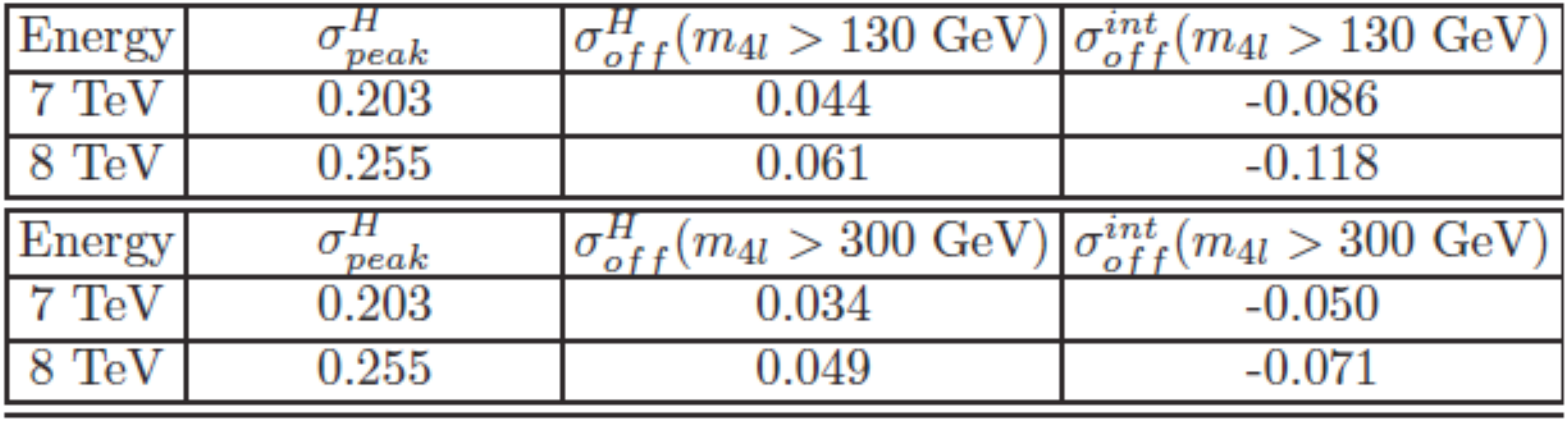
Summary

- With $3 ab^{-1}$, mass shift in ɣ ɣ will lead to an expected limit on width of $15\Gamma_{SM}$.
- MCFMv6.8 is a fast code for gg→ZZ→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 (N)NLO corrections to the $Z/\gamma^* Z/\gamma^* \rightarrow e^- e^+ \mu^- \mu^+$ process.
- WW process gives important complementary information and should be pursued too.

Backup

Quantifying the interference-comparison with CM

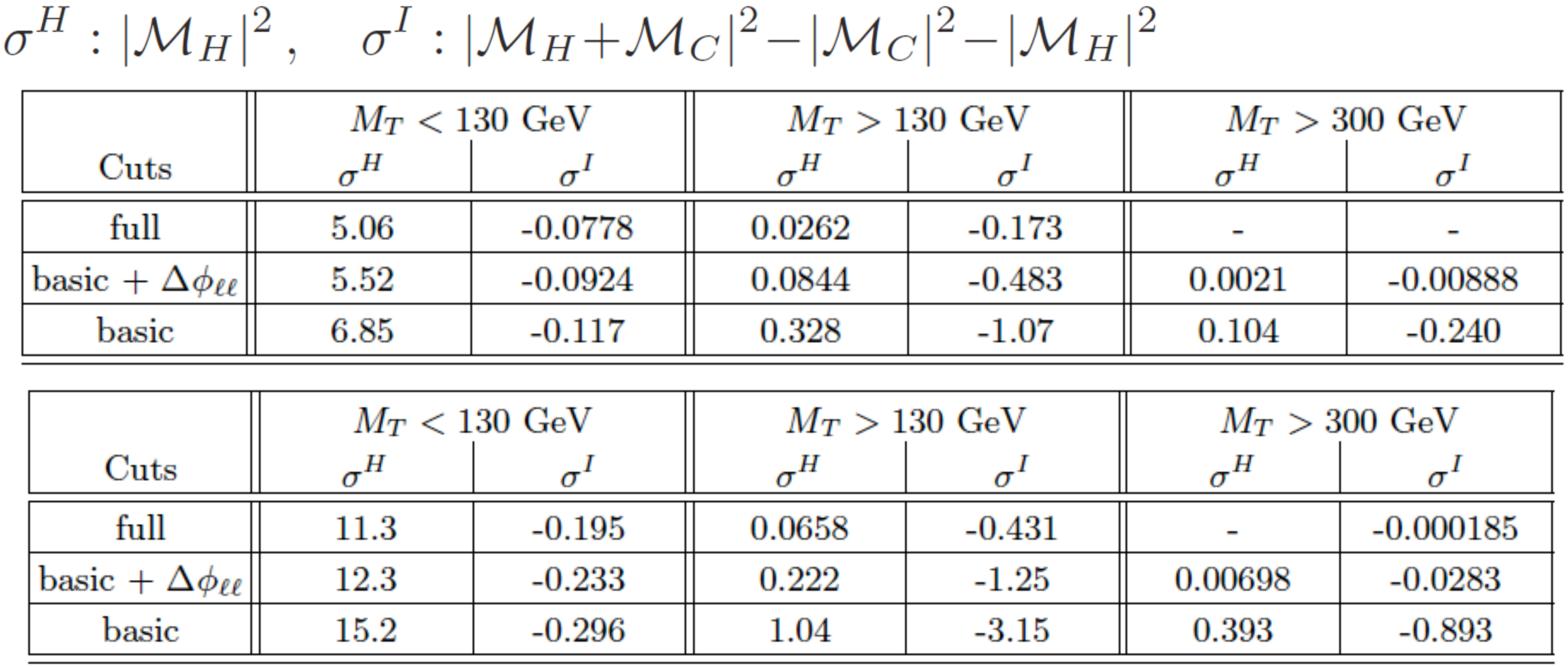
- Our results for interference differ (slightly) from CM paper.
- We believe that the reason is that CM used the double precision version of the Kauer code gg2VV, that contains a cut at $p_T<7$GeV, for continuum related pieces.



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

Energy	σ^{H}_{peak}	$\sigma^{H}_{off}(m_{4l} > 300\ \mathrm{GeV})$	$\sigma^{int}_{off}(m_{4l} > 300\ \mathrm{GeV})$
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 σ^H	$M_T < 130$ GeV σ^I	$M_T > 130$ GeV σ^H	$M_T > 130$ GeV σ^I	$M_T > 300$ GeV σ^H	$M_T > 300$ GeV 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 σ^H	$M_T < 130$ GeV σ^I	$M_T > 130$ GeV σ^H	$M_T > 130$ GeV σ^I	$M_T > 300$ GeV σ^H	$M_T > 300$ GeV 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 $ZZ \rightarrow e^- e^+ e^- e^+, \rightarrow \mu^- \mu^+ \mu^- \mu^+$
  - 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.