Bounding Higgs Width Through Interferometry

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in collaboration with Lance Dixon

LoopFest XII

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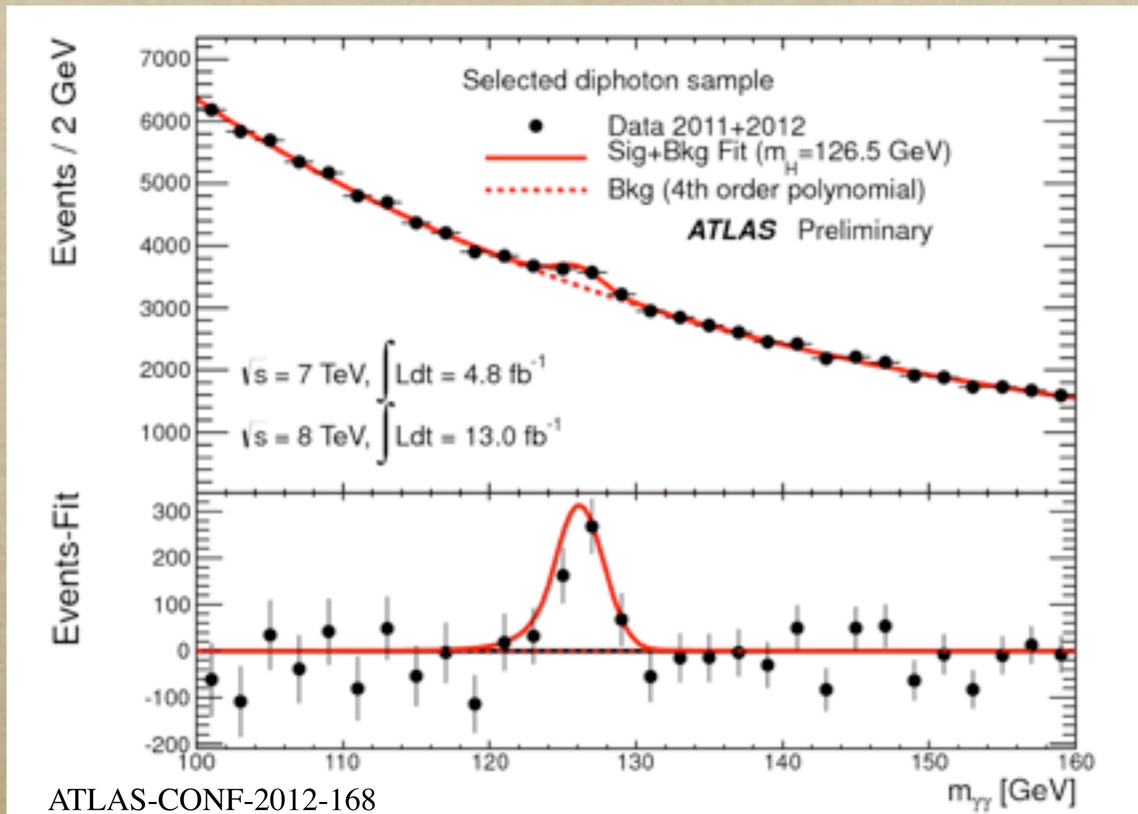

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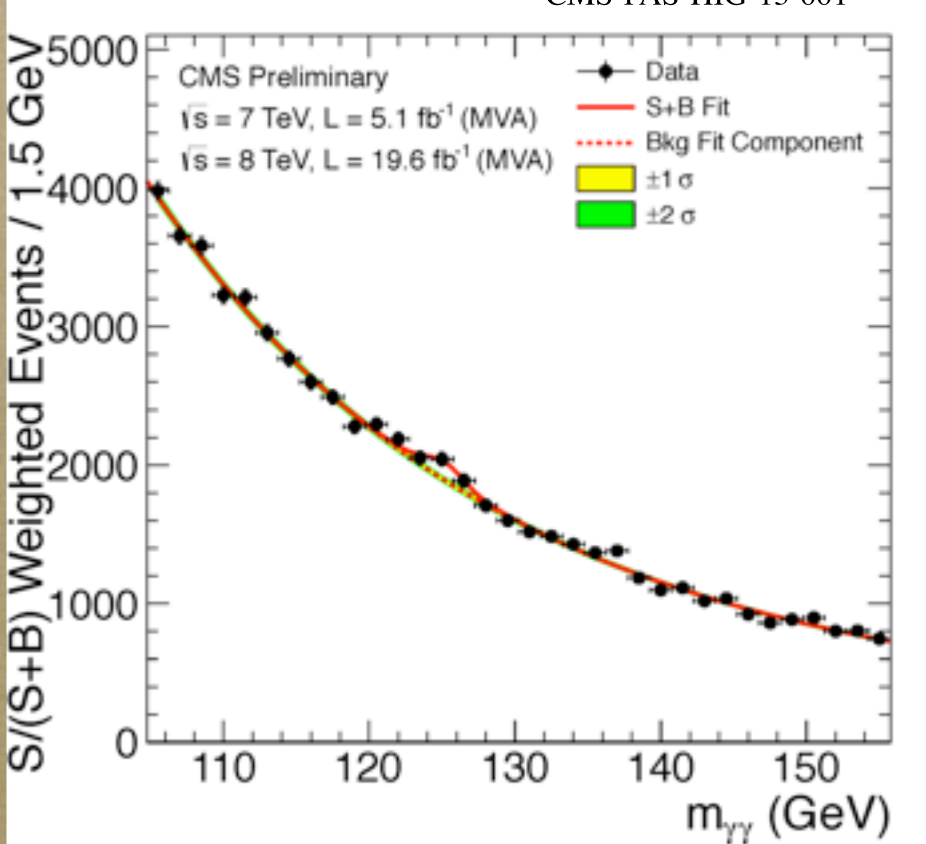


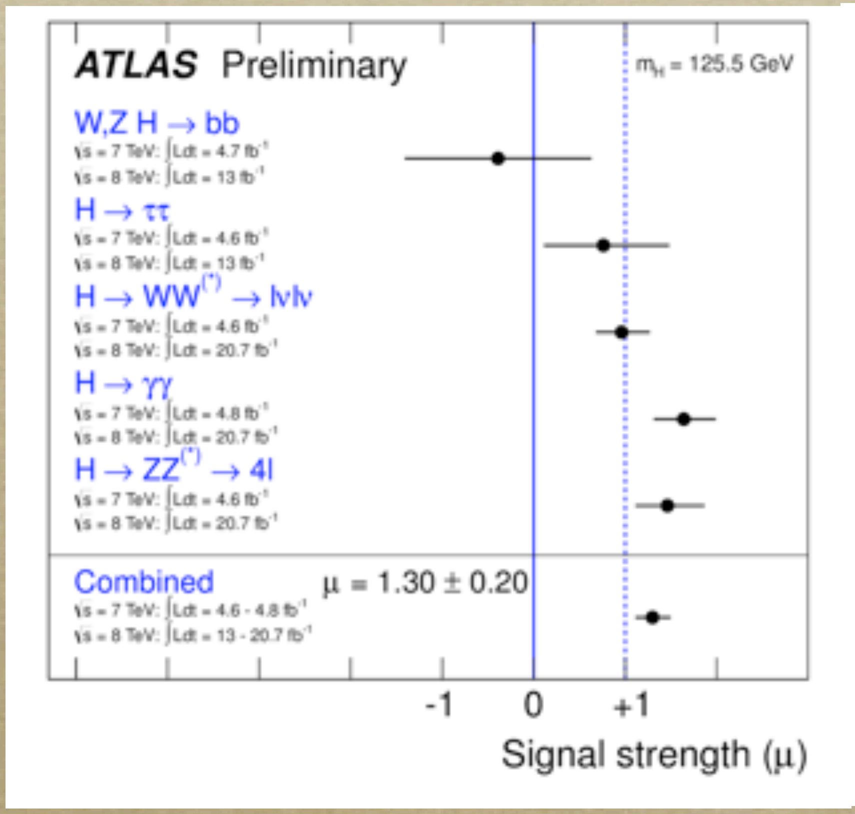
Higgs Boson Discovered!

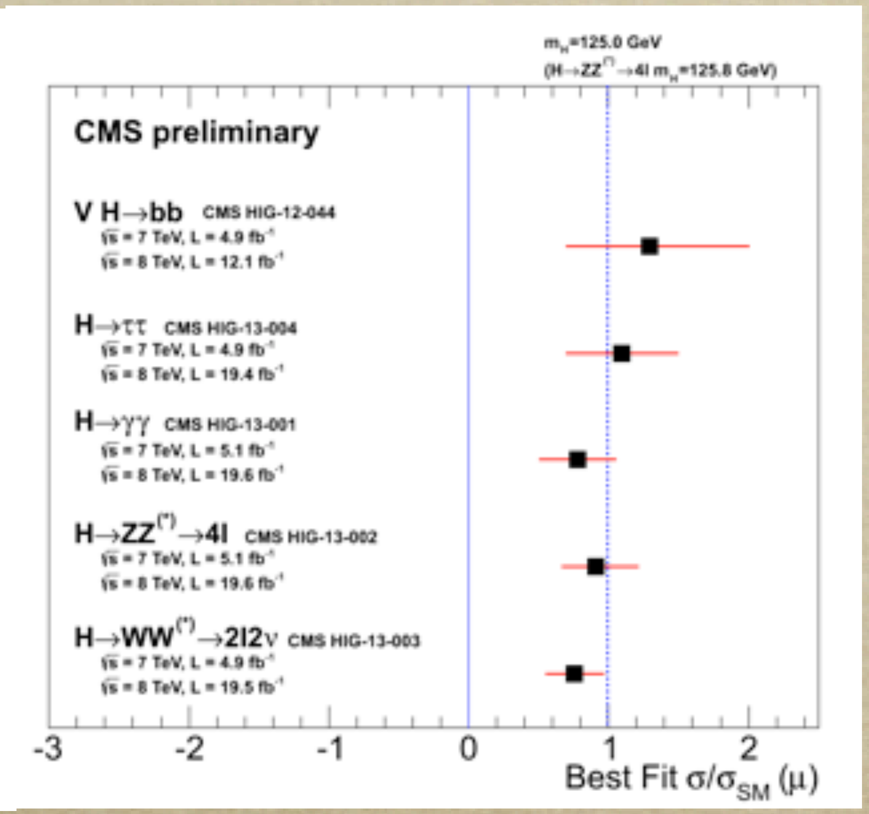
- *Biggest discovery in years*
- *Great achievement of SM*
- *Are we 100% sure?*

Outline

- *Interference in* $gg \rightarrow H \rightarrow \gamma\gamma$
- *Real part interference: mass shift*
- *NLO corrections to interference*
- *Bounding* Γ_H *using mass shift*
- *Non-SM Higgs: spin-2 scenario*
- *Conclusion*

Higgs Decay Channels





- *Produced primarily via gluon fusion*
- *Diphoton decay*
  - *small BR but clean*
  - *fully reconstructed invariant mass*
  - *large SM background*
  - *data in reasonable agreement with SM prediction*
- *Additional invisible decay channels increases Higgs total width*

Higgs Signal

- *Effective couplings of Higgs to gluons and photons*

NP correction

Unitarity bound: $|c_{g,\gamma}| \lesssim 26, 52$

$$\mathcal{L} = -\left[\frac{\alpha_s}{8\pi} c_g b_g G_{a,\mu\nu} G_a^{\mu\nu} + \frac{\alpha}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \frac{h}{v}$$

$b_{g,\gamma} = \frac{2}{3}, \frac{47}{9}$ at LO in heavy top/W limit

- *In narrow width approximation*

Always appears as a combo!

$$\sigma^{sig} = \int dM_{\gamma\gamma} \frac{S}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \sim \frac{c_g^2 c_\gamma^2}{\Gamma_H}$$

- *How to decouple width from couplings?*

Interference

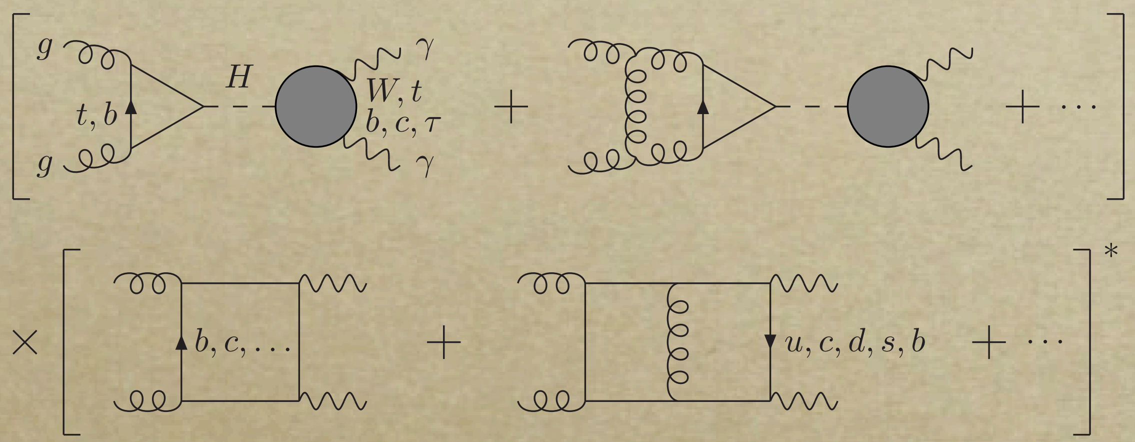
- *Interference with SM background in $\gamma\gamma$ channel*

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

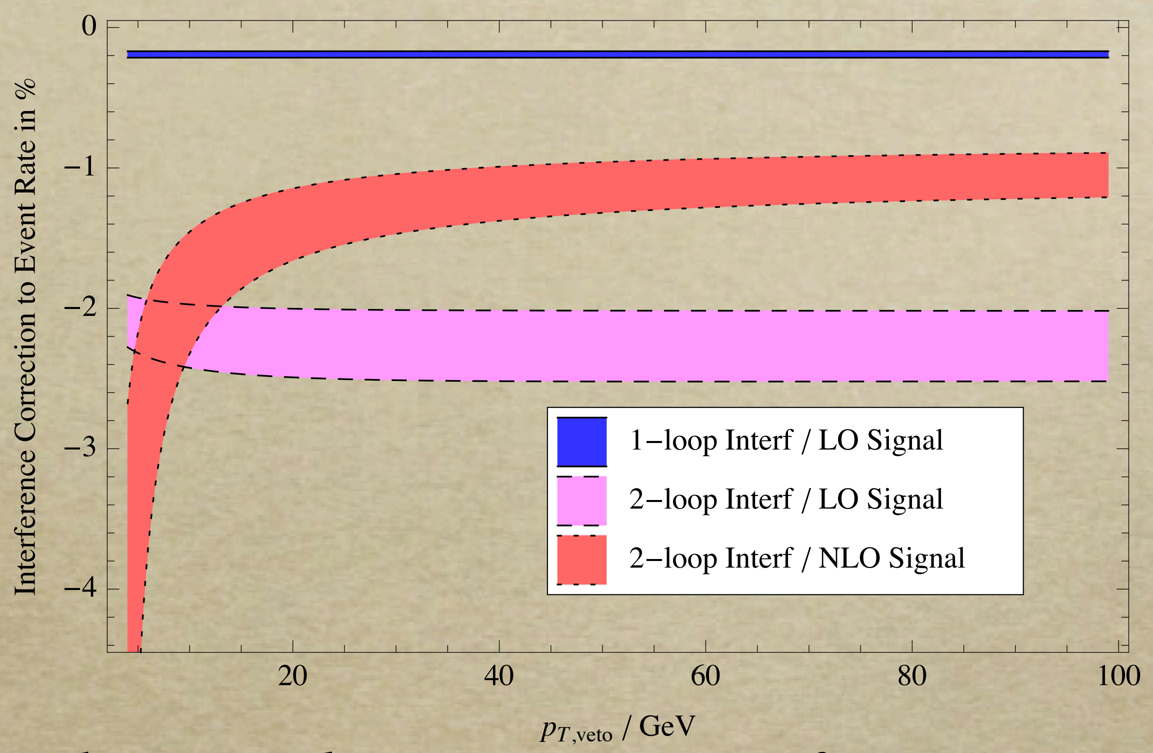
D.Dicus, S.Willenbrock, Phys.Rev.D37,1801

  - *real part of BW: asymmetric around Higgs peak, negligible contribution to integrated cross section given R doesn't vary too quickly*
  - *imaginary part of BW: constructive or destructive depending on the relative phase between signal and background*
    - *Integrated cross section of interference has different dependence on total width: suppressed by small Higgs width w.r.t pure signal*

Imaginary part of Interference



L.Dixon, M.Siu, hep-ph/0302233

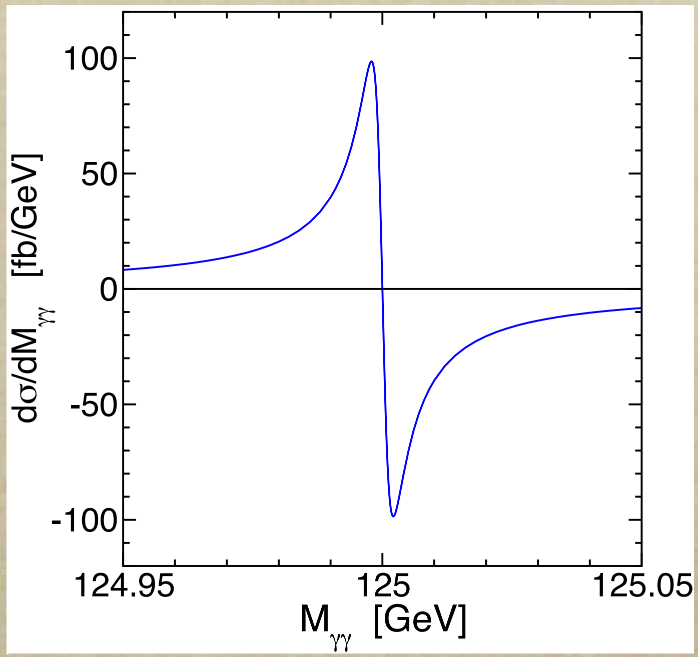


- *Signal amplitude predominantly real ⇒ need imaginary part from SM background for the relative phase*
- *SM continuum contribution starts at 1-loop*
  - *vanishing imaginary part in massless quark limit at LO*
  - *2-loop imaginary part leads to 1-2% destructive interference*
- *Too small an effect to see ...*

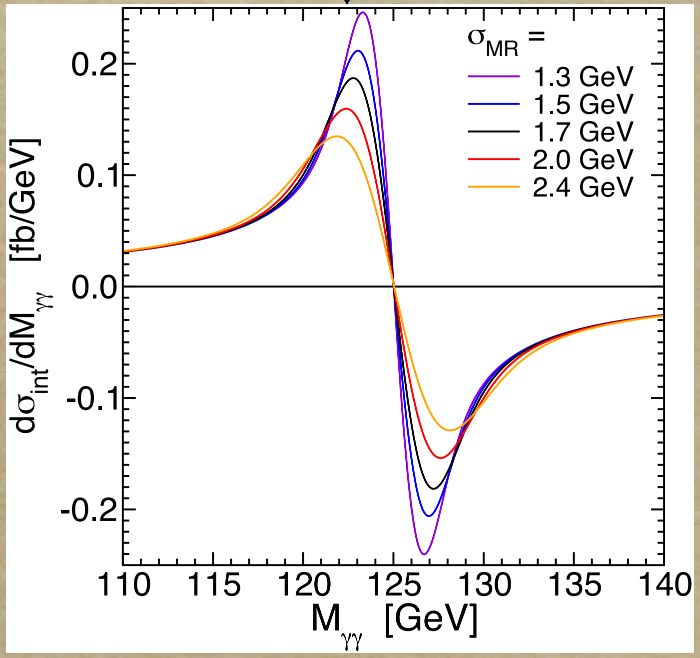
Theoretical uncertainty on signal~15%

LO Mass Shift

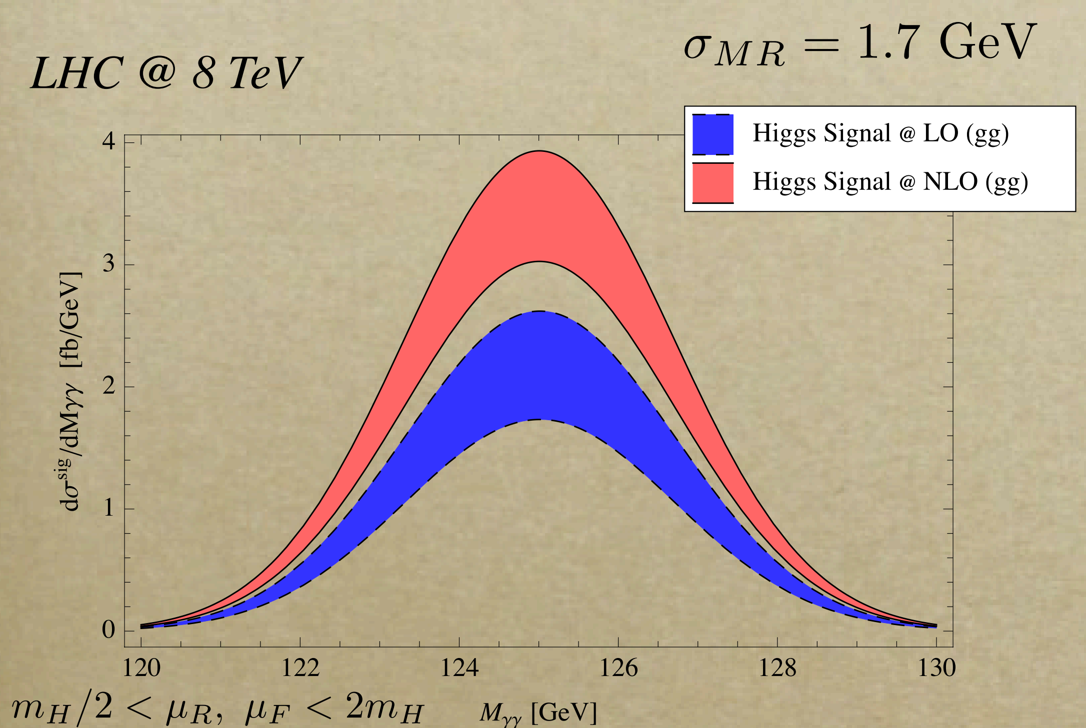
- *Real-part interference*
    - *non-vanishing at 1-loop with massless quarks*
    - *odd around Higgs mass ⇒ Higgs mass peak shift*
    - *asymmetric shape peaks/dips at $m_H \pm \Gamma_H/2$ ⇒ mass shift ~ Γ_H*
- *Different story when including effect of finite detector resolution*
    - *considerable contribution from Breit-Wigner tails*
    - *potentially visible shift of Higgs mass peak ~ 100 MeV*

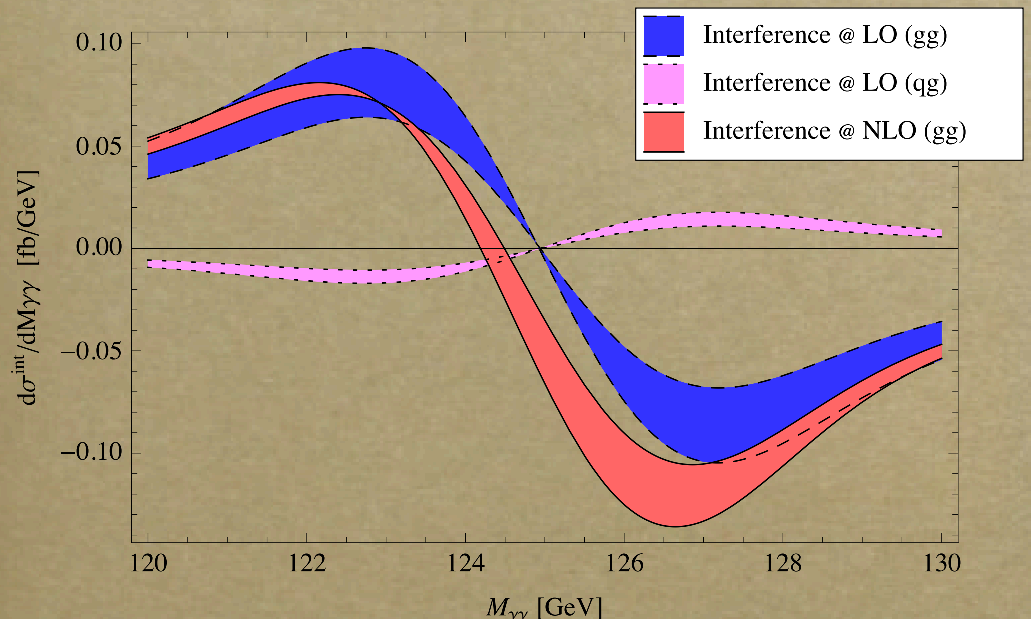


S.Martin, hep-ph/1208.1533



NLO QCD Correction



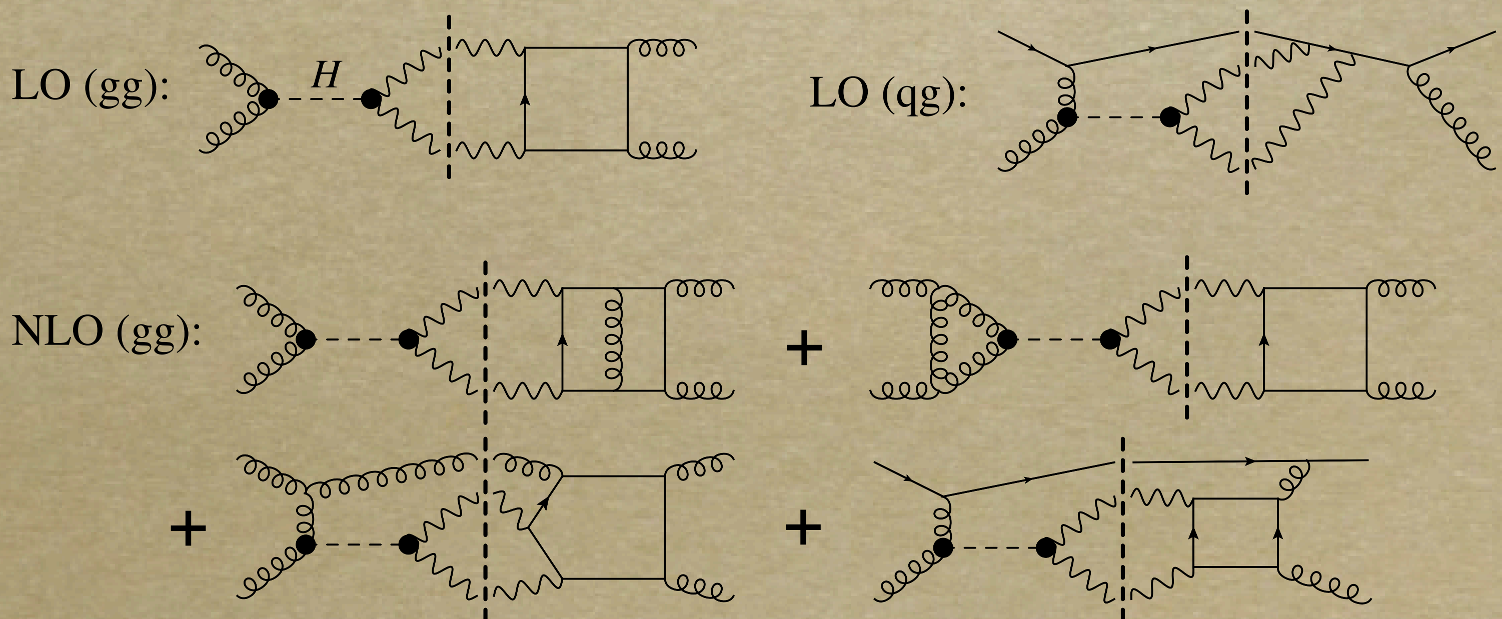


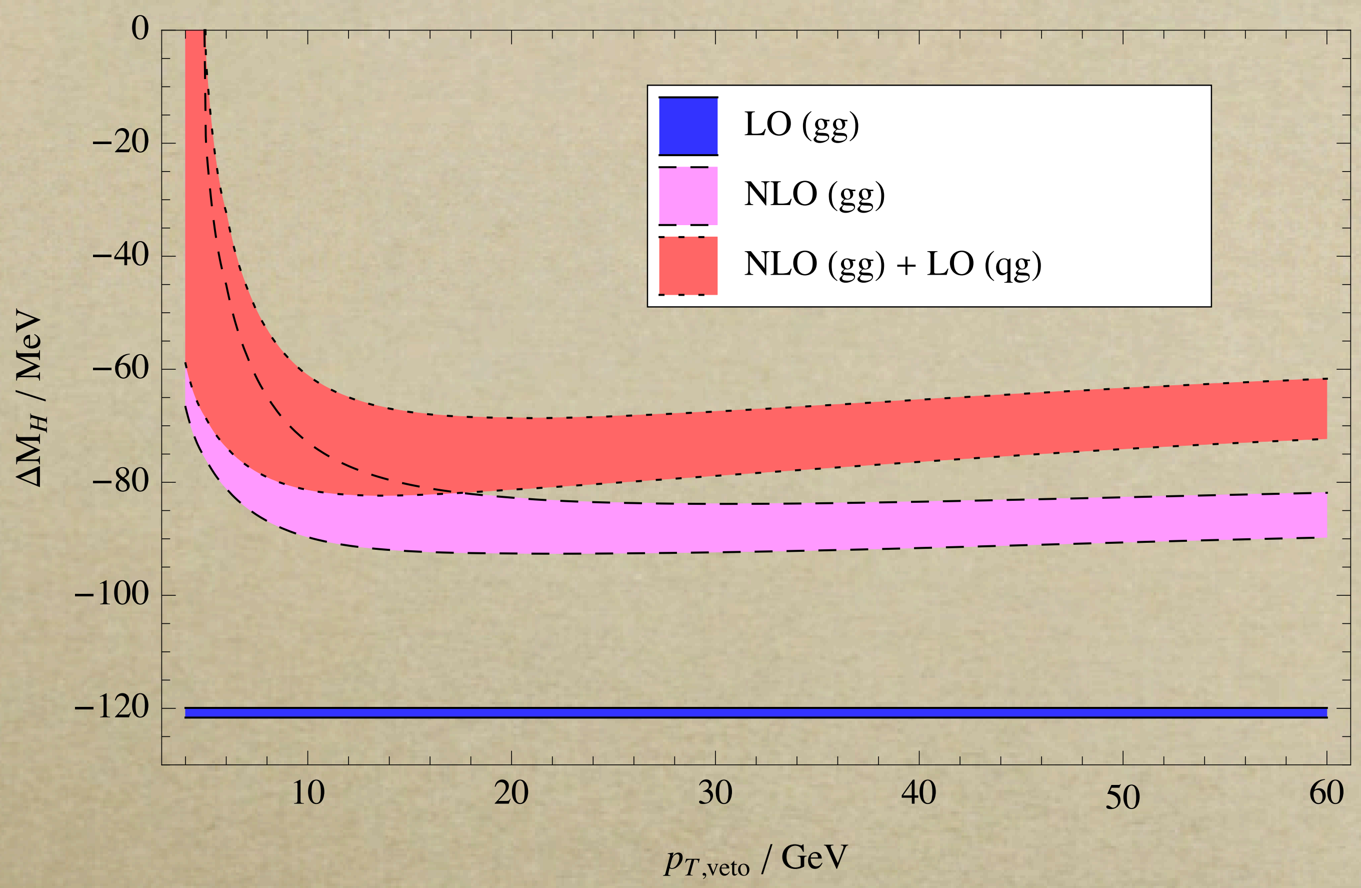
$p_{T,\gamma}^{\mathrm{hard/soft}} > 40/30$ GeV, $|\eta_\gamma| < 2.5$

Isolation: $\Delta R_{\gamma j} < 0.4$, $p_{T,j} > 3$ GeV

Veto jet : $p_{T,j} > 20$ GeV, $\eta_j < 3$

- *Known large K factor of Higgs production and SM background in QCD at NLO*
  - *more uncertainty when pT veto is involved*
- *Interplay between real and imaginary part of the interference leads to K factor depending on $M_{\gamma\gamma}$*
  - *imaginary part interference starts at 2-loop and is small*
  - *real part interference receives a relative constant K factor (~2 for inclusive case) between that of pure signal (~2.5) and background (~1.5)*





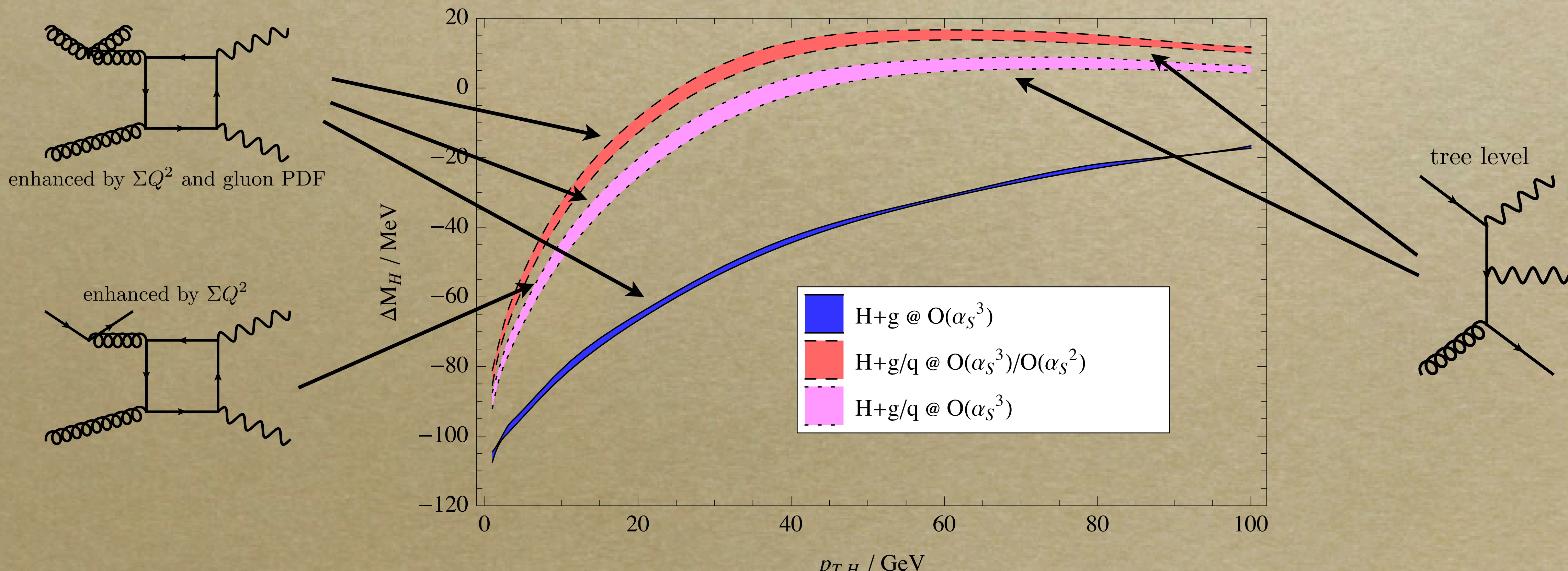
- *smaller background K factor ⇒ reduced mass shift*
- *extra contribution from the interference with tree level diagram in quark gluon channel, LO(qg), partly cancels with interference of gluon gluon channel, (N)LO(gg) ⇒ further reduces mass shift*

D. de Florian etc. hep-ph/1303.1397

- *mostly insensitive to pT veto choice because of large contribution from virtual correction*

Probing Mass Shift

- *Need a reference channel, ZZ*, to measure the shift: do it within $\gamma\gamma$ channel alone?*
- *Cancellation between qg and gg channels results in strong dependence on Higgs pT* S.Martin, hep-ph/1303.3342
- *Potentially observable with high luminosity data: better choice because experimental systematic uncertainty cancels*



Bounding Higgs Width

- *Mass shift sensitive to Higgs width due to modified couplings*
    - *must keep constant signal yields to be consistent with current experimental observation*

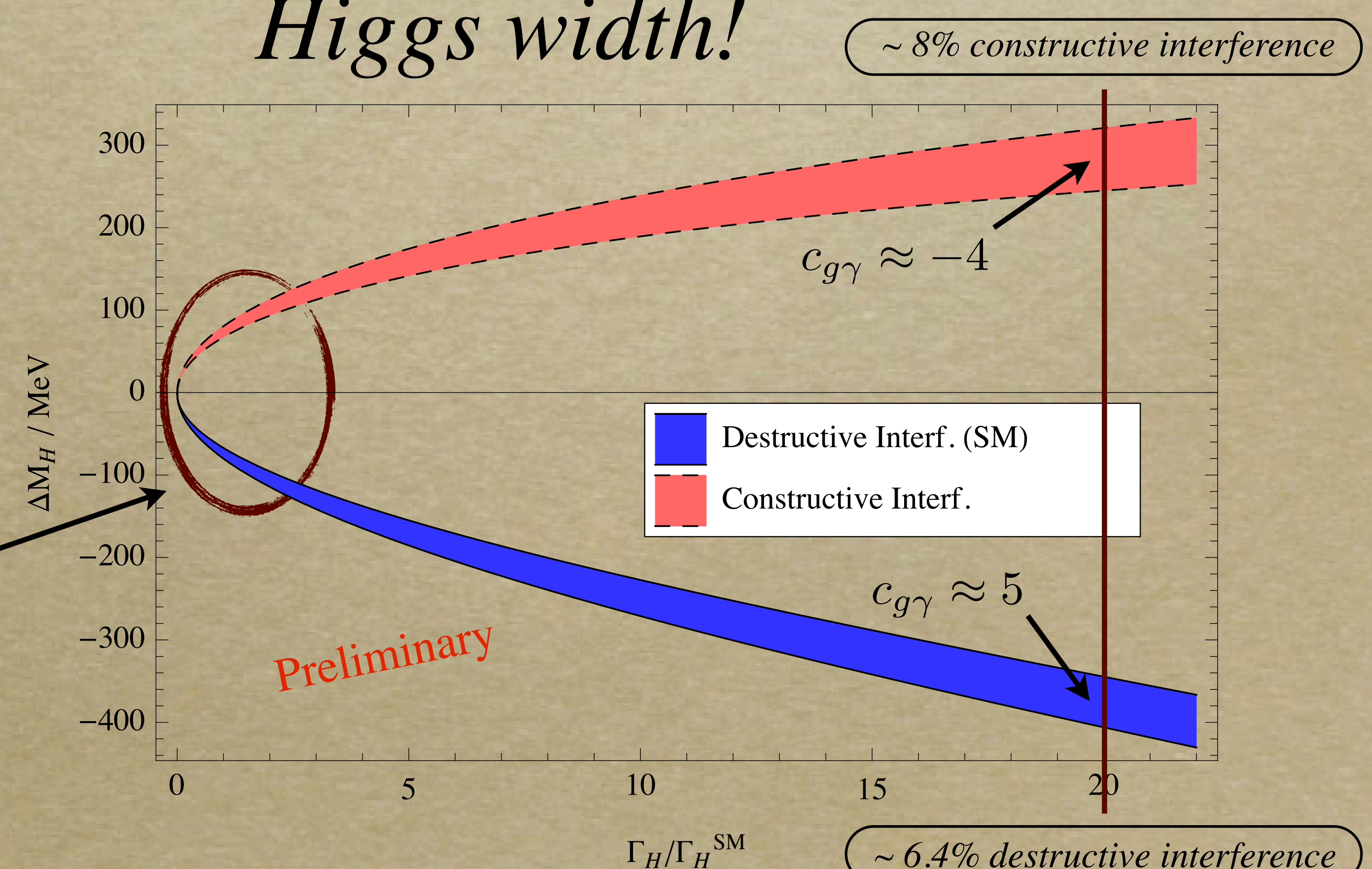
$c_{g\gamma} = c_g c_\gamma$

$$\frac{c_{g\gamma}^2 S(m_H)}{\Gamma_H} + c_{g\gamma} I(m_H) = \frac{S(m_H)}{\Gamma_H^{SM}} + I(m_H)$$

- *simple solution if vanishing destructive(constructive) interference*

$$|c_{g\gamma}| = \sqrt{\Gamma_H / \Gamma_H^{SM}}$$

- *In case NP flips the sign of Higgs amplitude ⇒ Constructive Interference*
- *Constrain/determine Higgs width!*



Summary

- *The interference of Higgs signal and SM continuum background allows the width to be measured separately from couplings experimentally*
- *Part of interference proportional to real part of BW propagator yields potentially observable mass shift with finite detector resolution*
- *Strong dependence of mass shift on finite Higgs pT provides way of detecting without reference to ZZ***
- *Increasing Higgs width leads to considerably larger mass shift and enhanced constructive/destructive interference*

- *The discussion so far applies to any CP-even spin-0 particles couples to SM similar to SM Higgs*
- *Could the observed "Higgs" be actually a spin-2 particle?*
  - *Analysis so far is performed with signal-only*
  - *Interference could modify angular distribution of diphoton final states*
  - *Possible large constructive/destructive interference to signal strength*
- *Will assume graviton-like (minimal) couplings for now*

Spin-2

- *The interference btw signal and background occurs with different helicity configurations (compared to spin-0 case)*
  - *Gluon and photon pairs have opposite helicity due to spin conservation*
  - *Thus non-vanishing imaginary part of SM background amplitude in massless quark limit at LO*
- *Graviton-like: photon and gluon couples to spin-2 particle via stress energy tensor*
  - *Dictates couplings to photon and gluon with the same sign*
  - *Also discuss couplings with different signs here for completeness*

Signal vs. Interference

Signal — *Interference - imaginary part* — *Interference - real part*

$$\overline{|\mathcal{A}|^2} = \left[\frac{G_{g\gamma}^2}{256} f_0(c) + \pi\xi M\Gamma f_i(c)\right]\frac{1}{(\hat{s}-M^2)^2+M^2\Gamma^2} + \xi f_r(c)\frac{\hat{s}-M^2}{(\hat{s}-M^2)^2+M^2\Gamma^2},$$

$$c = \cos\theta$$

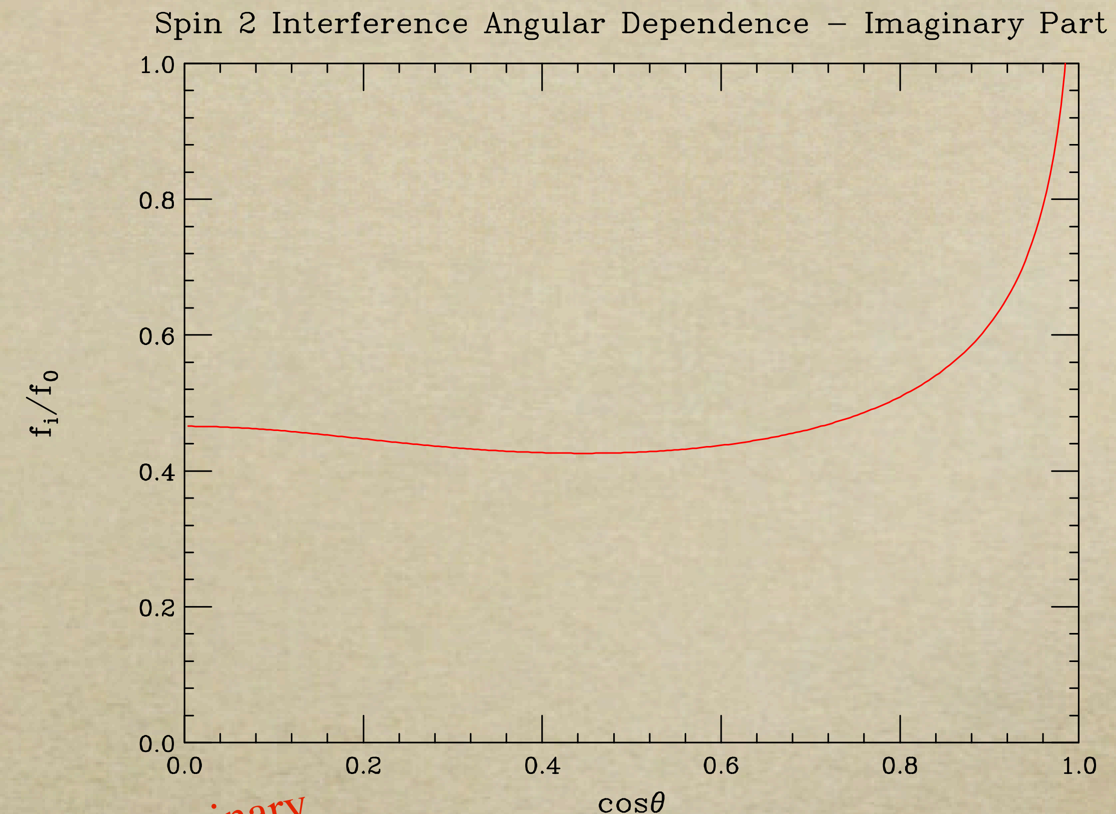
$$\xi = \frac{11}{72} G_{g\gamma}\alpha\alpha_s$$

$G_{g\gamma} > 0$ for heavy graviton

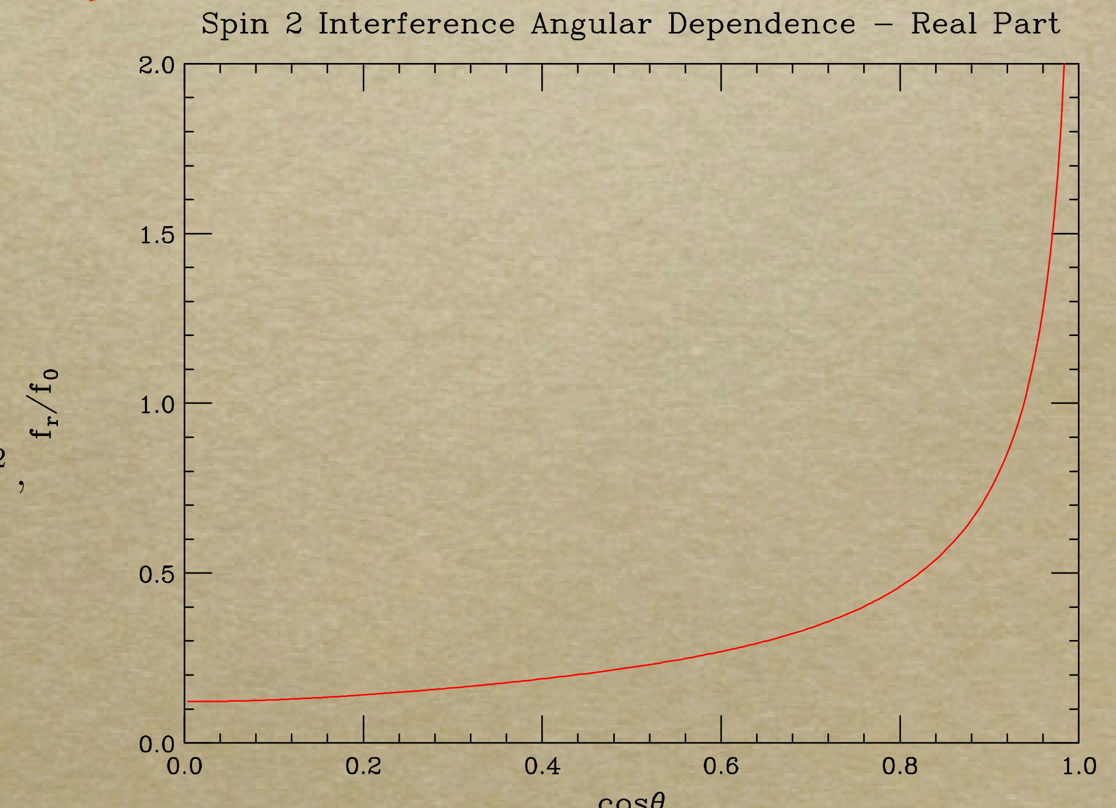
$$f_0(c) = 1 + 6c^2 + c^4,$$

$$f_i(c) = 2\left[\left(1+\frac{(1-c)^2}{4}\right)\ln\left(\frac{2}{1-c}\right) + \left(1+\frac{(1+c)^2}{4}\right)\ln\left(\frac{2}{1+c}\right)\right] - 3 + c^2,$$

$$f_r(c) = \left(1+\frac{(1-c)^2}{4}\right)\ln^2\left(\frac{2}{1-c}\right) - \frac{(1+c)(3-c)}{2}\ln\left(\frac{2}{1-c}\right) + \left(1+\frac{(1+c)^2}{4}\right)\ln^2\left(\frac{2}{1+c}\right) - \frac{(1-c)(3+c)}{2}\ln\left(\frac{2}{1+c}\right) + 1 + c^2,$$



Preliminary

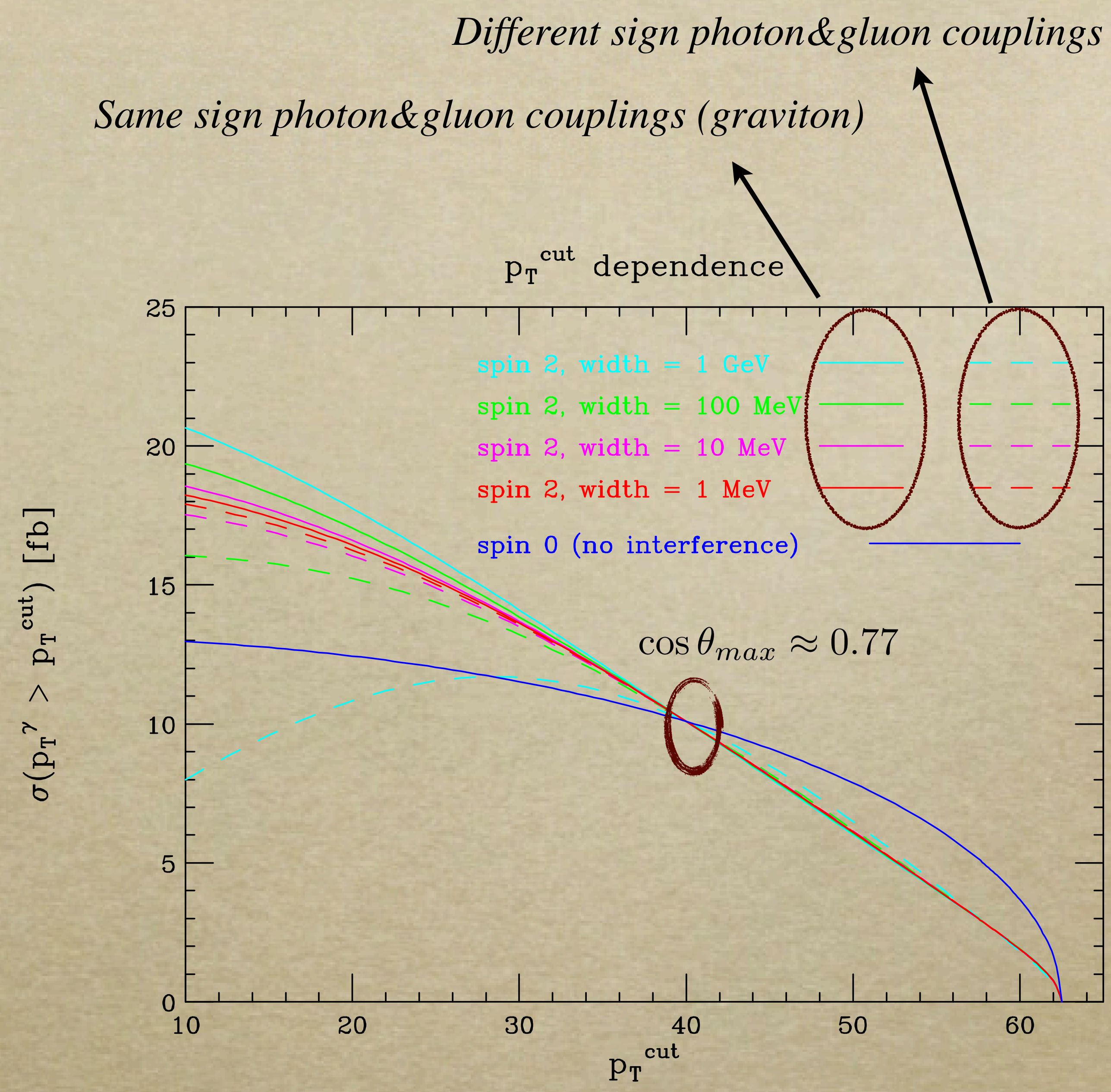


Relatively similar angular dependence in central region

- *Normalize the spin-2 coupling so that signal yield is the same as the SM Higgs*
  - *Need non-zero photon pT cut for finite interference contribution in spin-2 case*
  - *Choose pT_{cut} = 40 GeV to solve for $G_{g\gamma}$ by equating the yields for spin-0 and spin-2*
- *Moderate pT cut limits photon to central region*

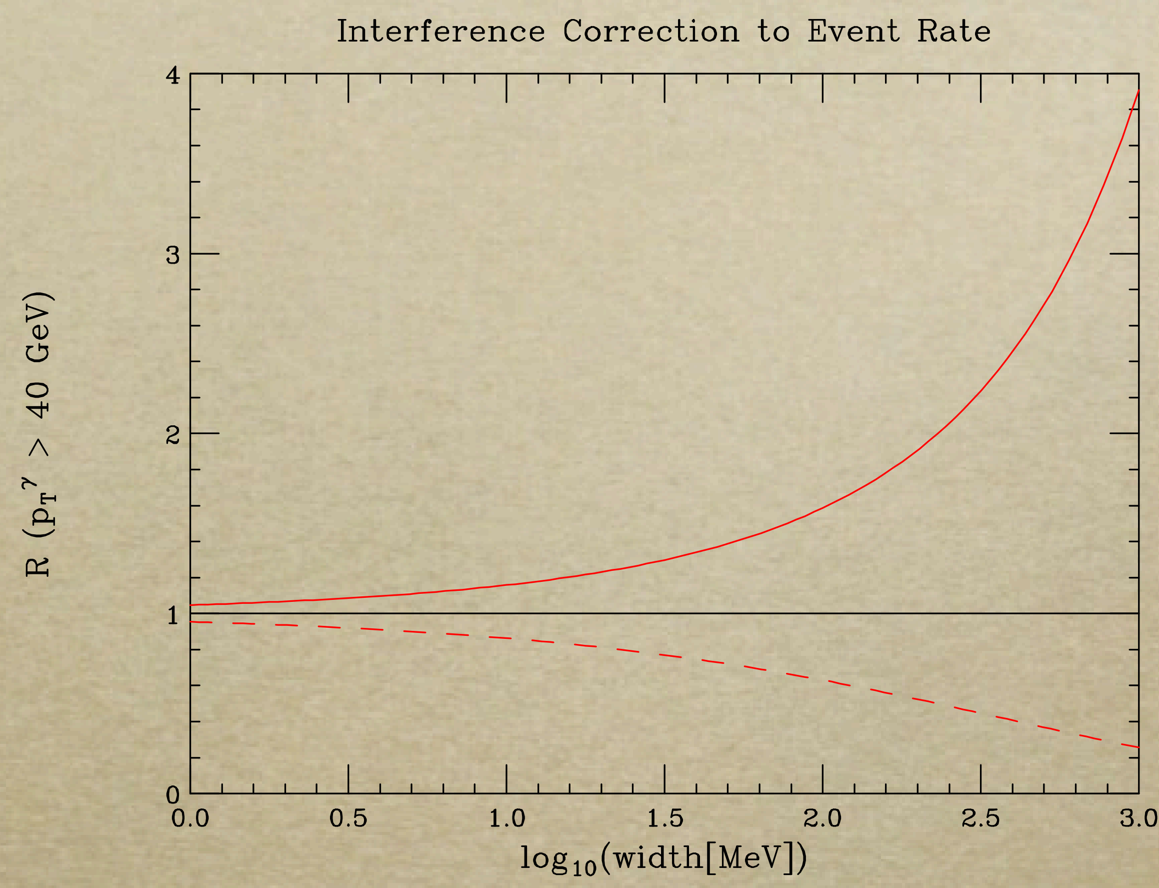
$$\cos\theta_{max} = \sqrt{1-(2p_T^{cut}/M)^2}$$

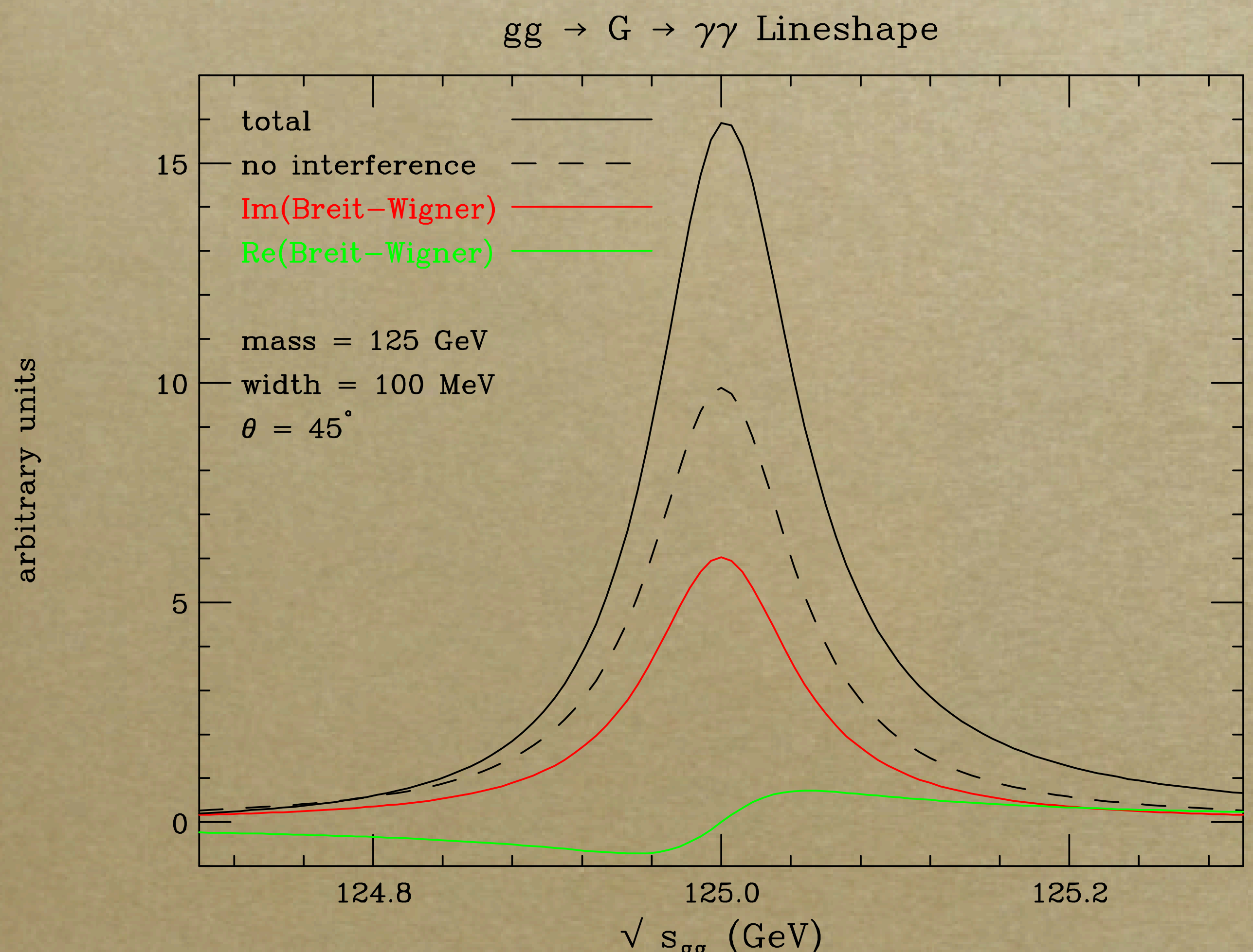
  - *pT_{cut} = 40 GeV : signal-only angular distribution analysis largely unaffected by interference*



Interference on Signal Yields (Spin-2)

- *Strong constructive/ destructive interference at large width*





- *for Γ = 100 MeV : O(1) correction to signal yields (~50%)*
- *Affect the coupling measurement in spin-2 interpretation*

Future Work

- *Continue study of interference with jets: important due to strong dependence on finite pT in Higgs case*
  - *Calculation implemented in Sherpa for further analysis with MC@NLO*
  - *Higher order correction with resummation helpful for future precision studies*
- *Possible large interference in the $Z\gamma$ channel*
  - *Constructive/Destructive interference starts at LO (1-loop)*
  - *Large background from DY potentially generate considerable interference contribution*
- *What role Interference plays in Higgs production via vector boson fusion?*

Future Work

- *Expect similar K factor for signal, interference and background in spin-2 scenario*
  - *LO analysis should hold*
- *Spin-2 with jet: part of NLO QCD correction*
  - *large constructive/destructive effect: dependence on finite pT?*
  - *effect on angular distribution with finite pT*
- *Cases other than minimal couplings (graviton-like) needed to be examined*
- *Imperative to extend analysis to Higgs with mixed CP states*
  - *changes relative sign between signal and background amplitude*
  - *study currently in progress*

Conclusion

- *The interference in Higgs diphoton decay channel provides additional degree of freedom to constrain/measure Higgs width*
- *Interference can also be used to probe other properties of Higgs: spin, CP ...*