Bounding Higgs Width Through Interferometry

work with:
Lance Dixon *- 1305.3854*
Lance Dixon *and* ***Stefan Höche*** *- ongoing*

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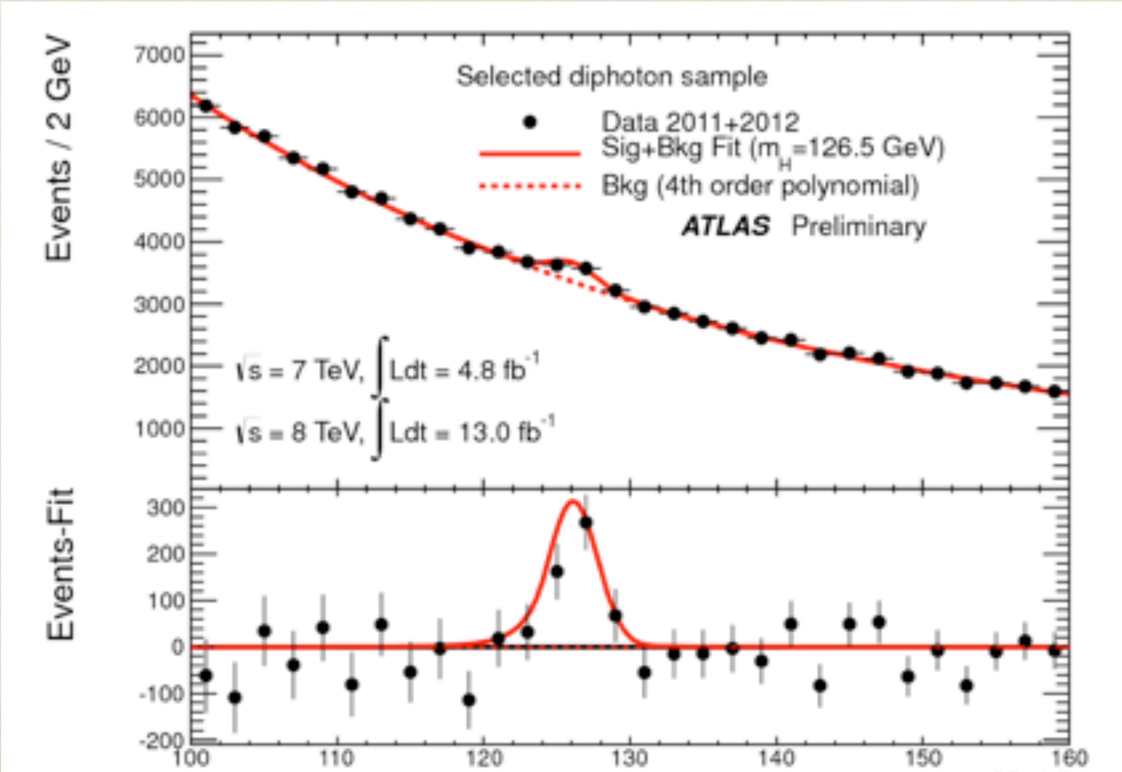

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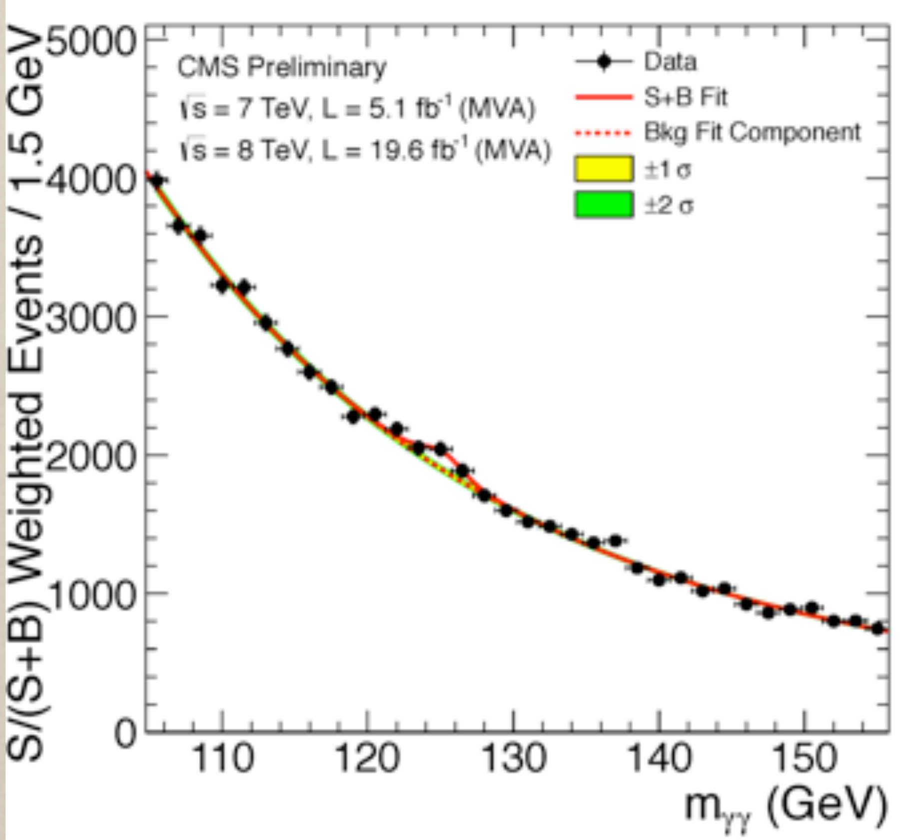


Higgs Boson Discovered!

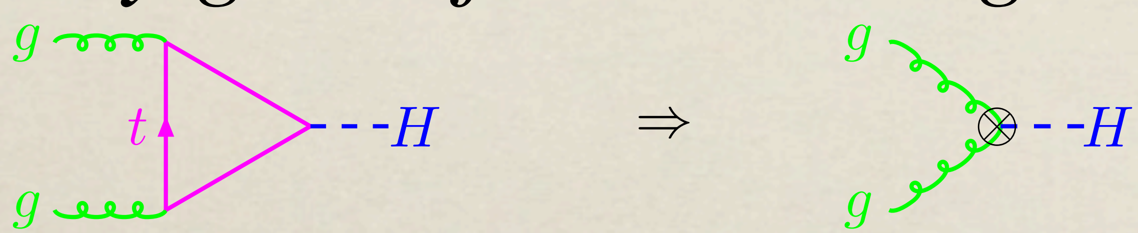
- *Biggest discovery in years*
- *Great achievement of SM*
- *How much can we learn about Higgs from LHC?*

Outline

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

Higgs Production

- *Dominated by gluon fusion through a top quark loop*



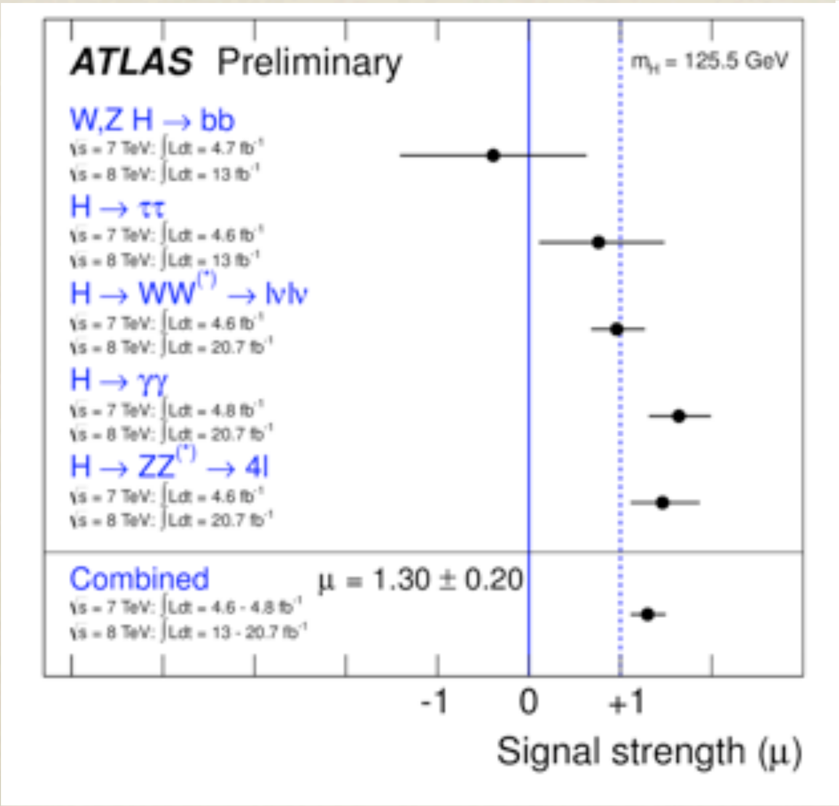
- *To make higher order correction feasible, approximate top quark loop by effective ggH vertex*
- *Similarly, photon couples to Higgs through top quark and W boson loop, can also be approximated by effective $\gamma\gamma H$ vertex*

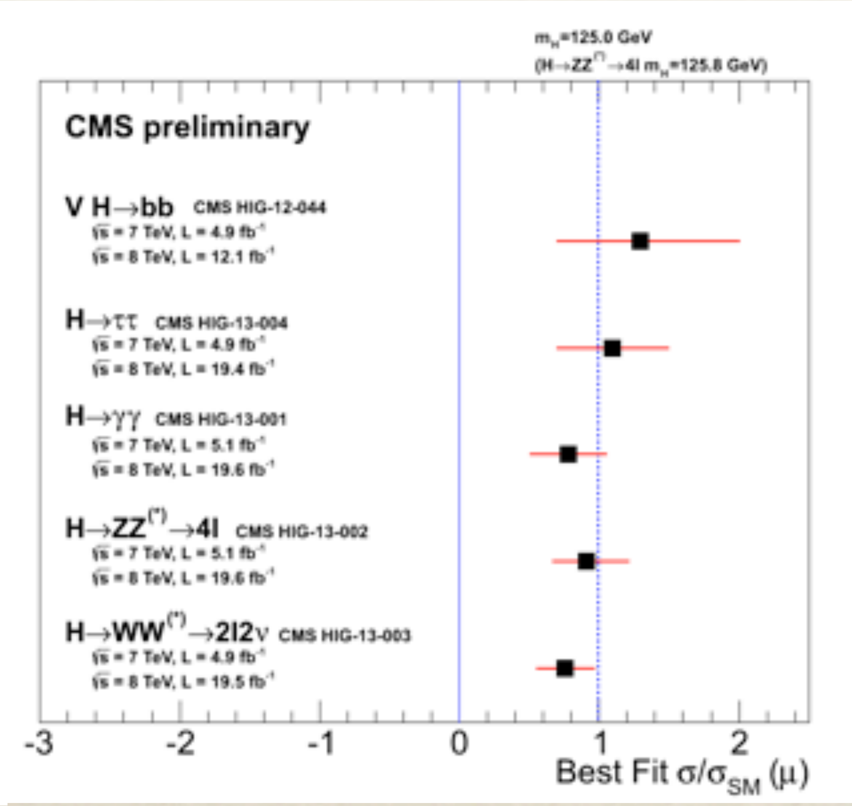
$\mathrm{SM:}\ b_{g,\gamma} = \frac{2}{3}, \frac{47}{9}$ at LO in heavy top/W limit

new physics correction

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

Higgs Decay





- *For $m_H \sim$ 125GeV, Higgs resonance is weak*
- *Diphoton decay*
  - *excellent experimental photon energy resolution ⇒ γγ signal visible even though Br(H→γγ) ~ 0.0023*
  - *fully reconstructed invariant mass*
  - *large SM background*
  - *data in reasonable agreement with SM prediction*
- *Additional invisible/undetectable decay channels could increase Higgs total width and reduce γγ BR*

Full Diphoton Amplitude

- *Gluon pair to diphoton full amplitude*

$$\mathcal{A}_{gg\to\gamma\gamma} = -\frac{\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}}{M_{\gamma\gamma}^2 - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\rm cont}$$

$$\mathcal{A}_{gg\to H} \propto c_g$$
$$\mathcal{A}_{\gamma\gamma\to H} \propto c_\gamma$$

- *Higgs signal appears as resonance in diphoton invariant mass $M_{\gamma\gamma}$ spectrum*

$$S \sim |\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}|^2$$

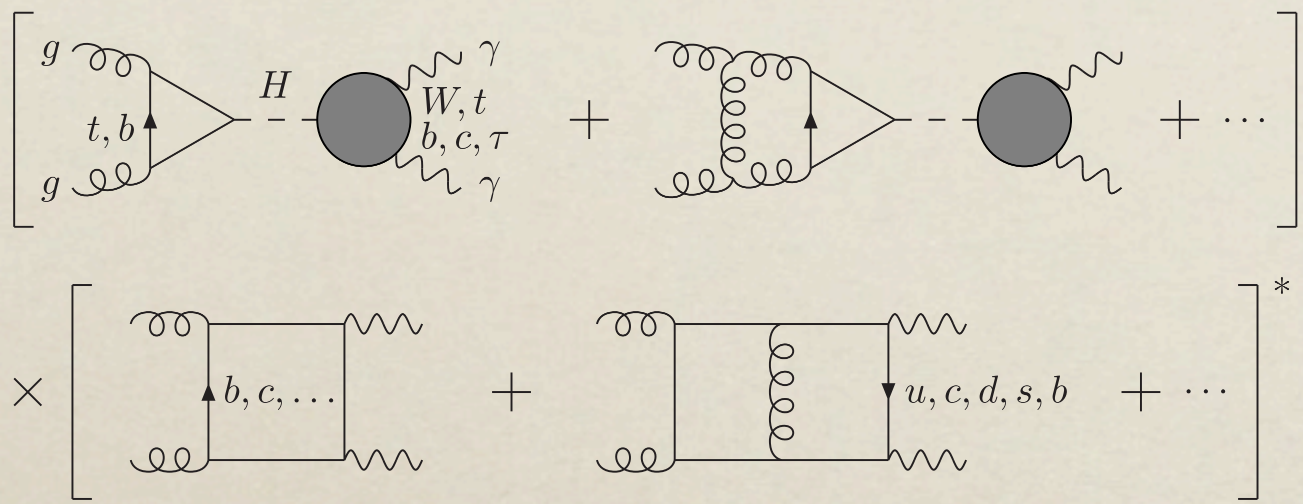
- *Signal strength in narrow width approximation*

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

→ *Always appears as a combo!*

- *In SM, all Higgs properties dictated by m_H, how well can we test them at LHC?*
- *Need to decouple width from couplings in LHC*

Interference



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

- *The interference contribution*

$$-2m_H\Gamma_H \frac{\mathrm{Im}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})}{(M^2_{\gamma\gamma}-m^2_H)^2+m^2_H\Gamma^2_H} -2(M^2_{\gamma\gamma}-m^2_H)\frac{\mathrm{Re}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})}{(M^2_{\gamma\gamma}-m^2_H)^2+m^2_H\Gamma^2_H}$$

- *Integrated cross section of interference term has different dependence on total width: suppressed by small Higgs width w.r.t pure signal*

$$\sigma^{int} = \int dM_{\gamma\gamma}\frac{(M^2_{\gamma\gamma}-m^2_H)R+m_H\Gamma_H I}{(M^2_{\gamma\gamma}-m^2_H)^2+m^2_H\Gamma^2_H} \sim c_g c_\gamma$$

$R \sim \mathrm{Re}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})$

$I \sim \mathrm{Im}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})$

Interference

- *Interference has two pieces*

$$R \sim \mathrm{Re}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})$$
$$I \sim \mathrm{Im}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\mathrm{cont}})$$

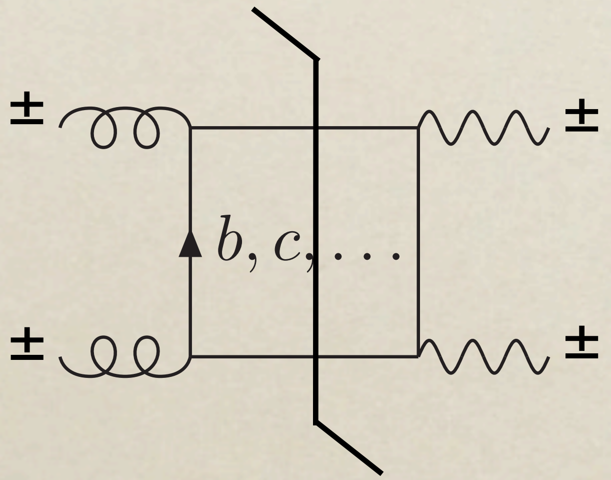
$$\sigma^{int} = \int dM_{\gamma\gamma} \frac{(M^2_{\gamma\gamma} - m^2_H)R + m_H\Gamma_H I}{(M^2_{\gamma\gamma} - m^2_H)^2 + m^2_H\Gamma^2_H} \sim c_g c_\gamma$$

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

  - *Real part of Breit-Wigner: asymmetric around Higgs peak, negligible contribution to integrated cross section given that R doesn't vary too quickly*
  - *Imaginary part of Breit-Wigner: constructive or destructive depending on the relative phase between signal and background*

Imaginary part of Interference

$\mathcal{A}^{\rm tree}(g^\pm g^\pm \to q\bar{q}) = \mathcal{A}^{\rm tree}(q\bar{q} \to \gamma^\pm\gamma^\pm) = 0$ for $m_q = 0$



$$I \sim \mathrm{Im}(\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}\mathcal{A}^*_{\rm cont})$$

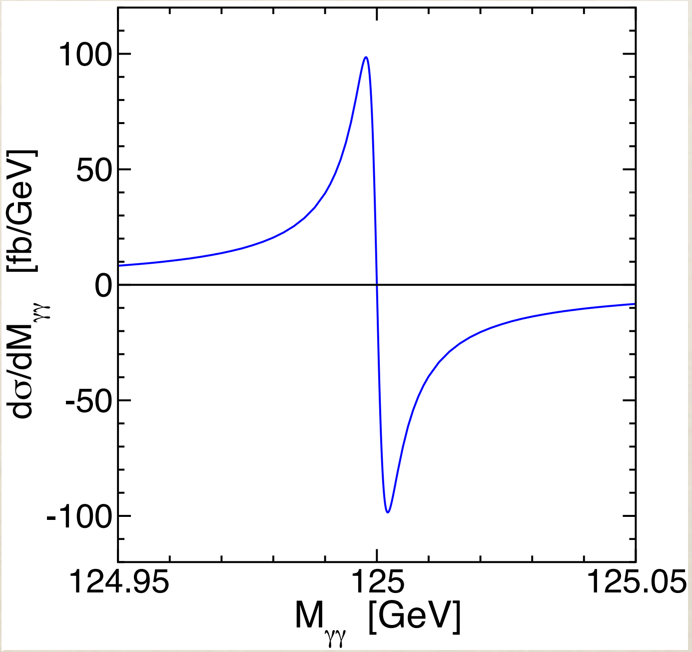
- *The full ggH and $\gamma\gamma H$ amplitudes are dominantly real for $m_H<2m_t,2m_W$ as top and W contribute most to the effective couplings; small imaginary part from light quark loops is suppressed by Yukawa couplings*

- *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%

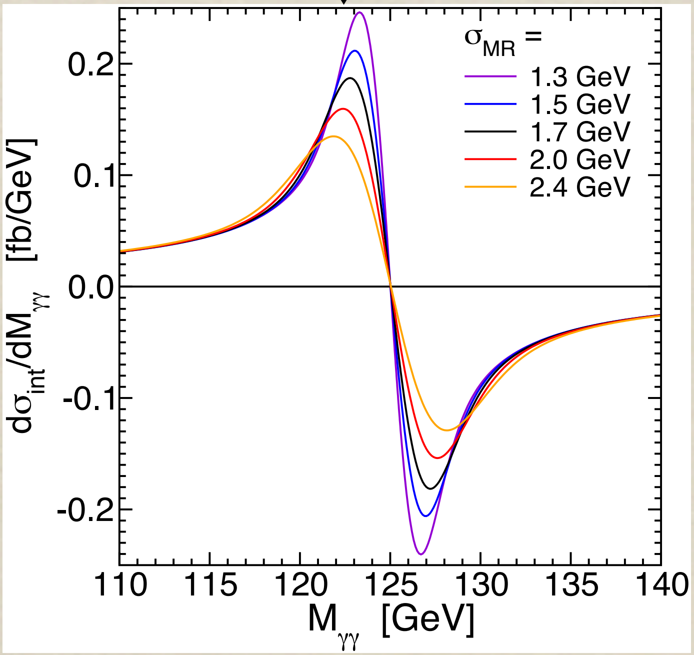
LO Mass Shift

Interference only (LO)



- *Real-part interference*
  - *non-vanishing at 1-loop with massless quarks*
  - *odd around Higgs mass ⇒ Higgs mass peak shift*
  - *generically, asymmetric shape peaks/dips at $m_H \pm \Gamma_H/2$ ⇒ mass shift ~ Γ_H*

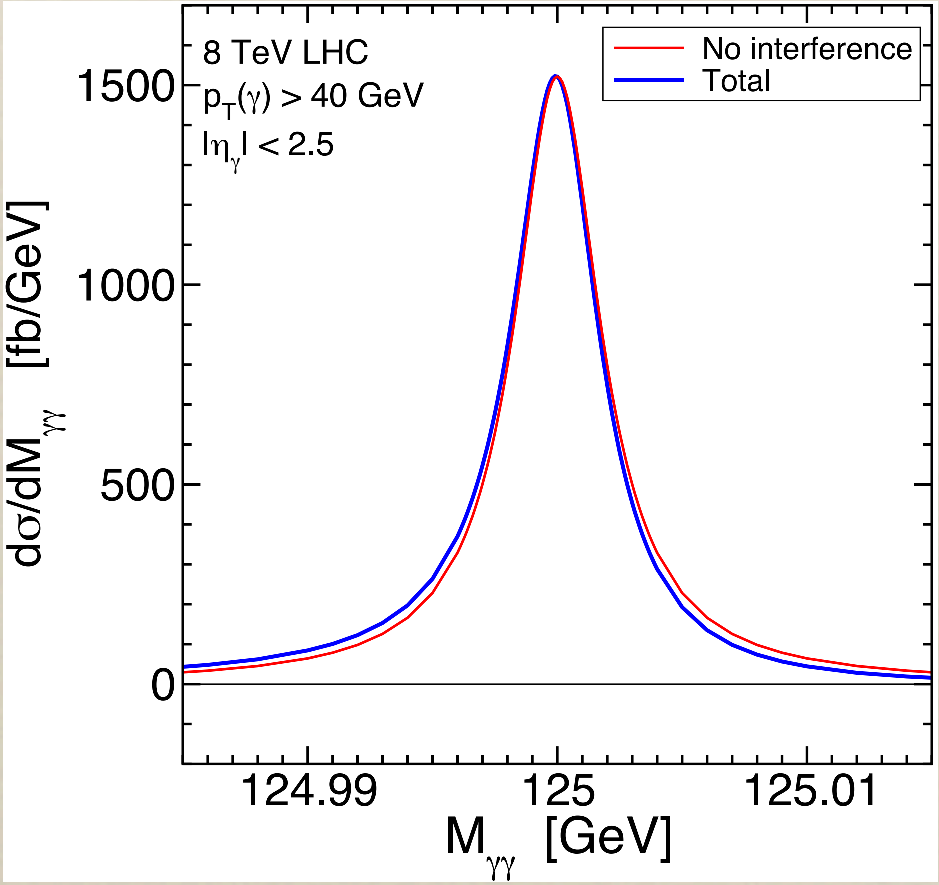
S.Martin, hep-ph/1208.1533

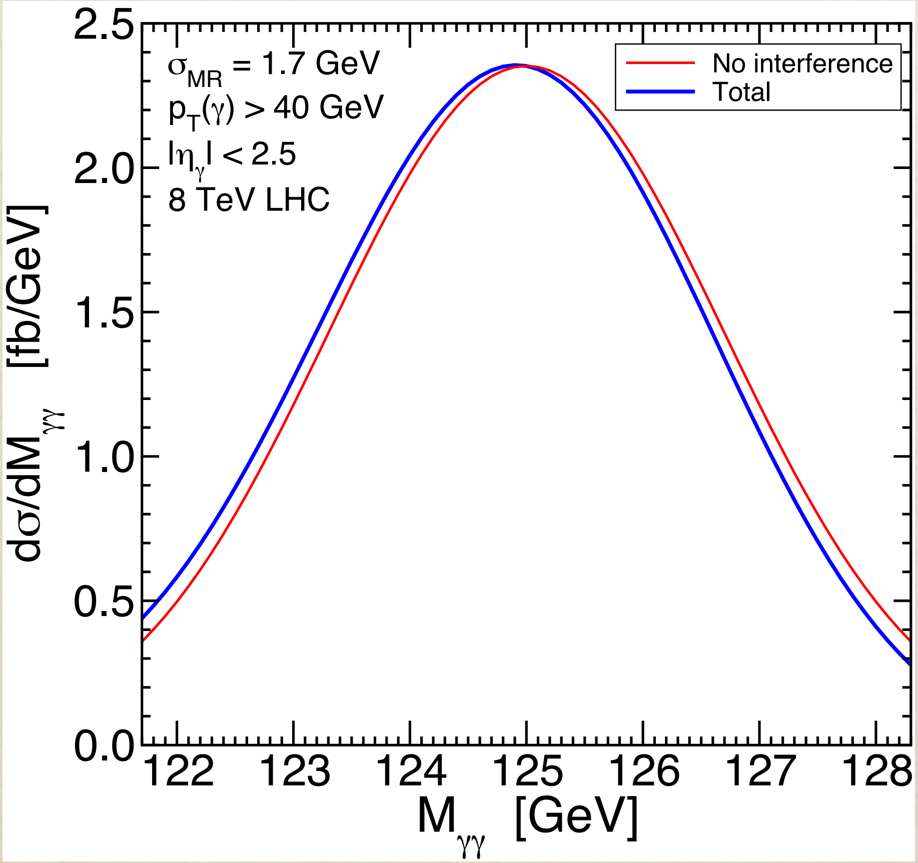


- *Different story when including effect of finite detector resolution*
  - *considerable contribution from Breit-Wigner tails*
  - *potentially visible shift of Higgs mass peak ~ 100 MeV*

LO Mass Shift

S.Martin, hep-ph/1303.3342

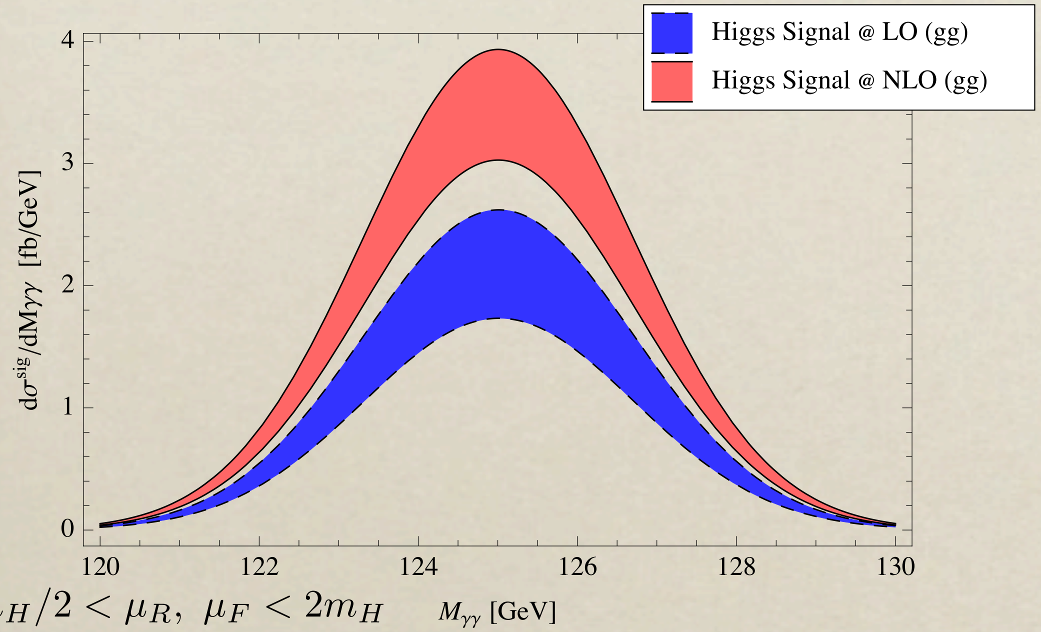




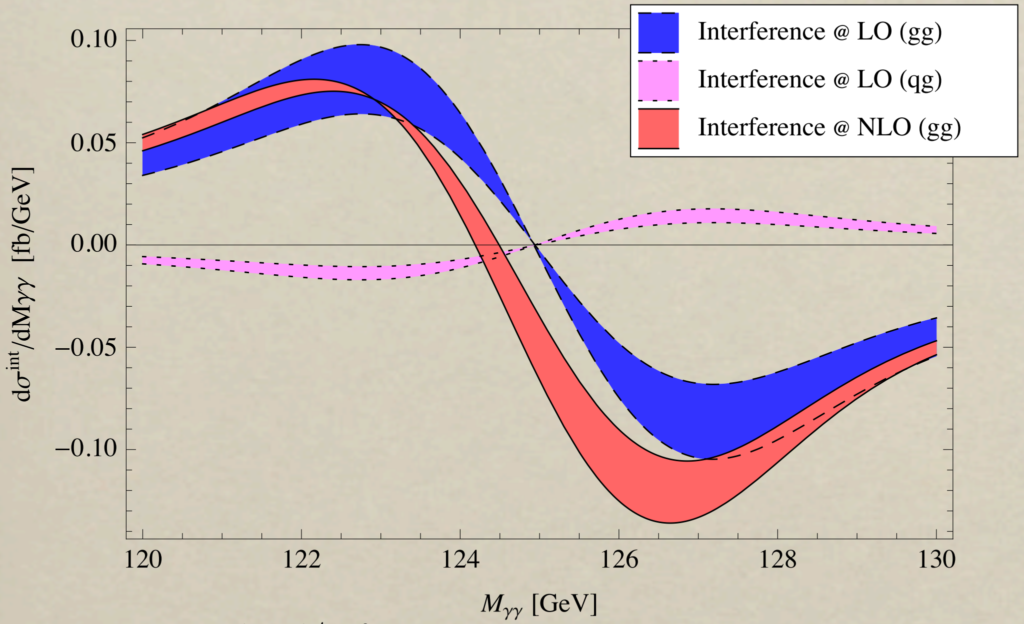
NLO QCD Correction

LHC @ 8 TeV

$\sigma_{MR} = 1.7$ GeV



$m_H/2 < \mu_R,\ \mu_F < 2m_H$

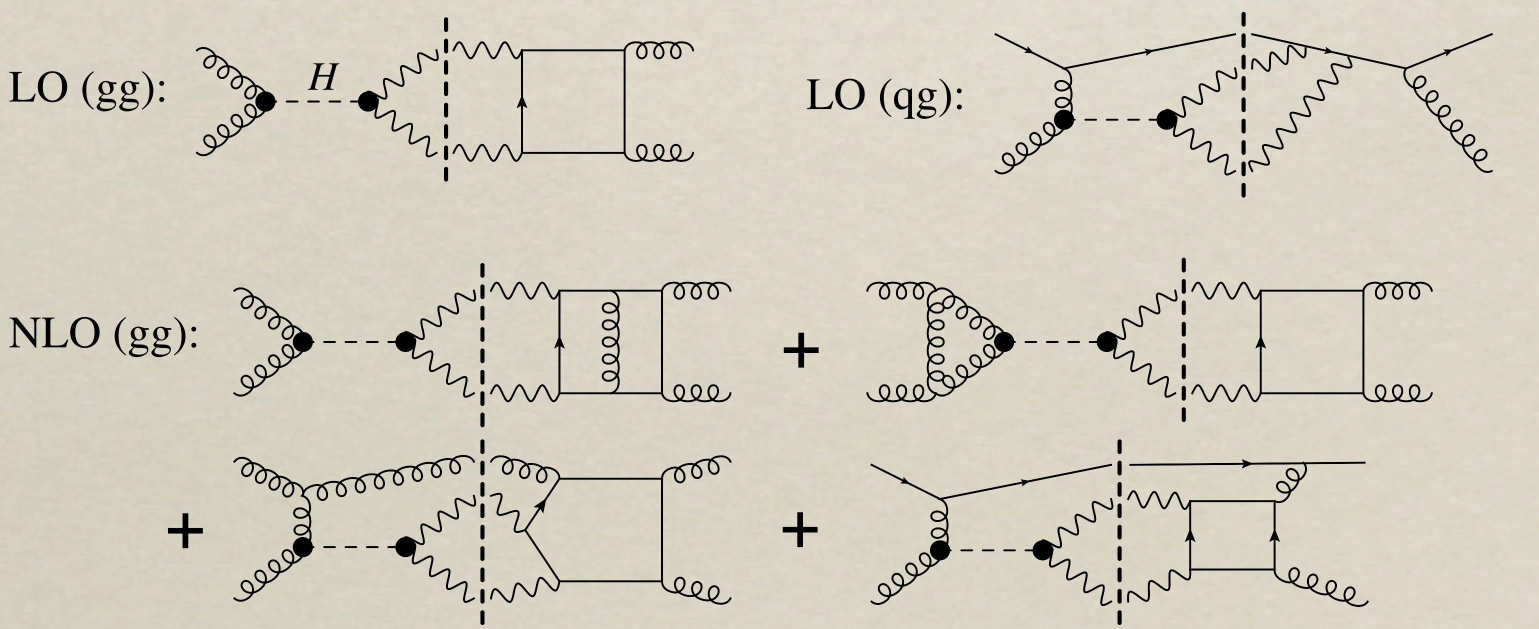


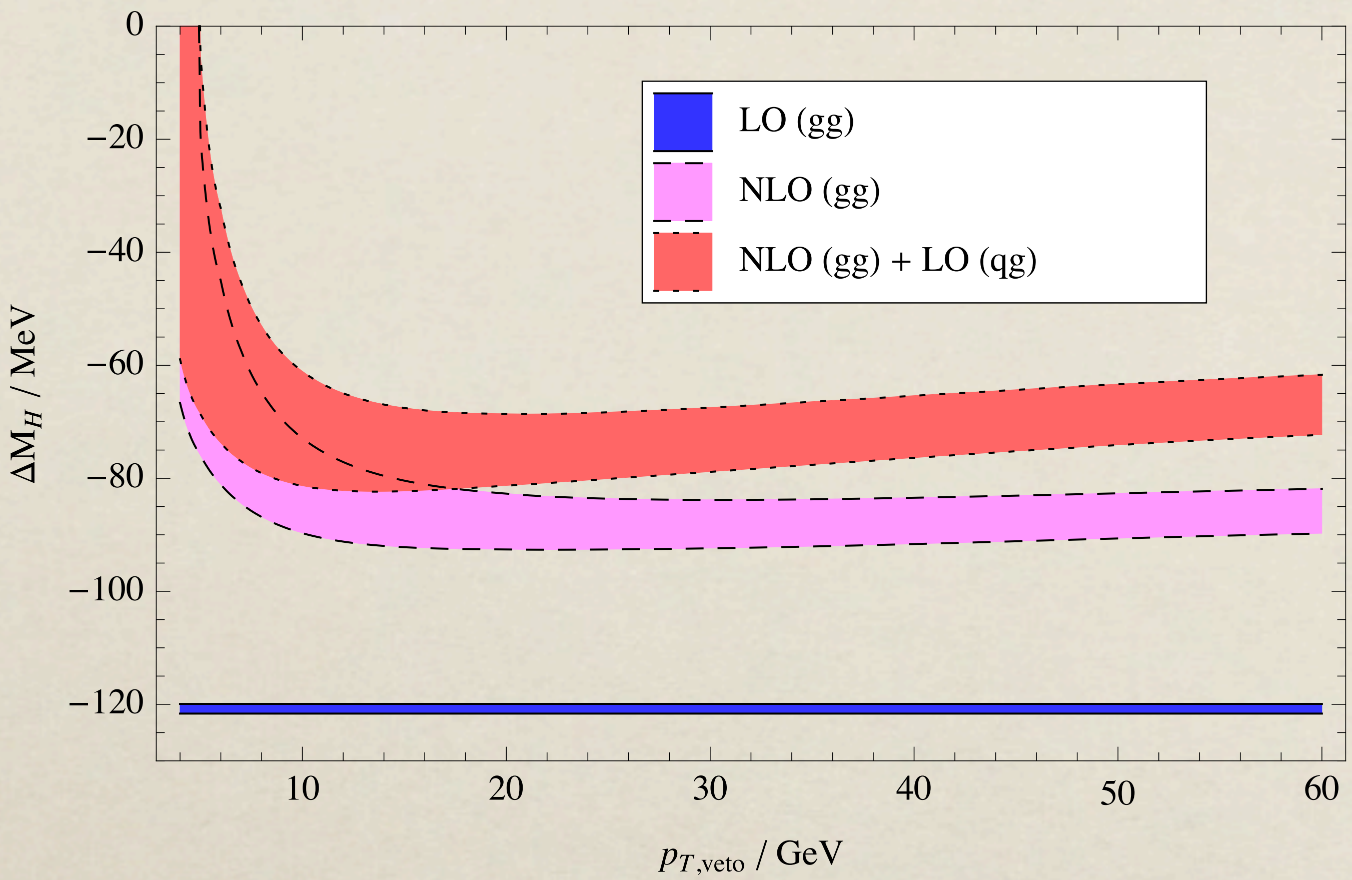
$p_{T,\gamma}^{\mathrm{hard/soft}} > 40/30$ GeV, $|\eta_\gamma| < 2.5$

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)*





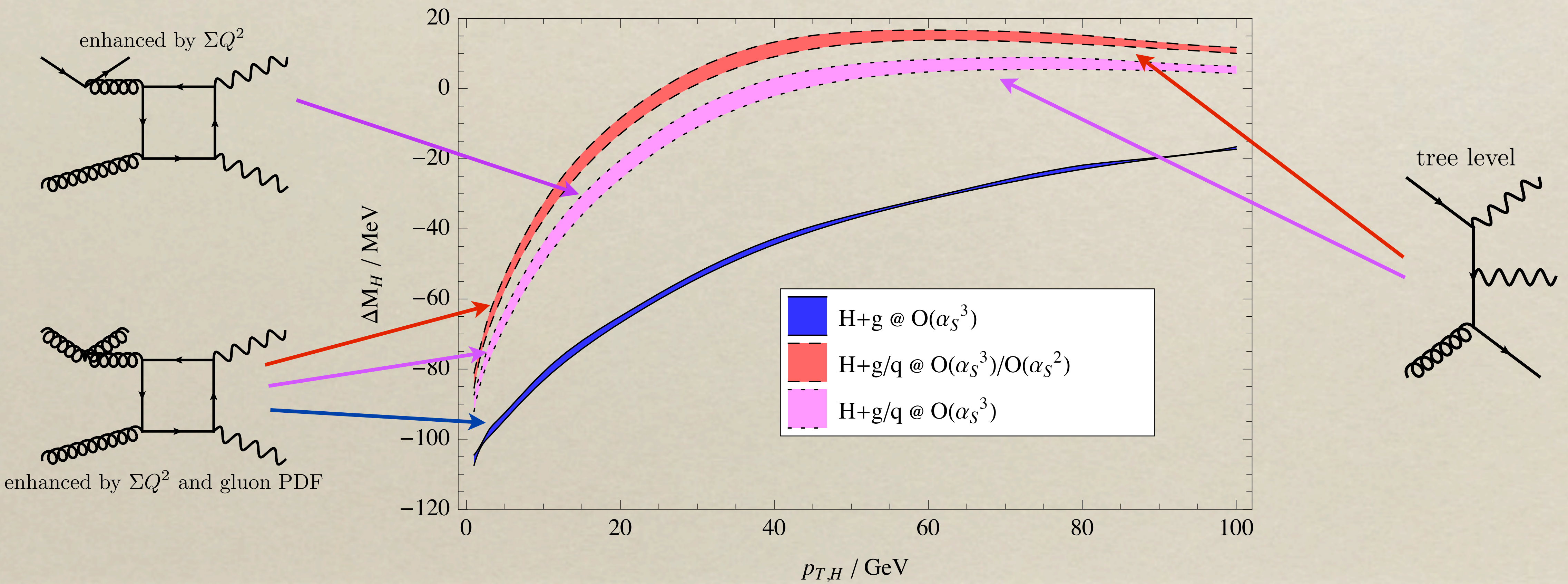
- *smaller background K factor ⇒ reduced mass shift*
- *with radiation, the extra contribution from the interference with tree level diagram in quark gluon channel, LO(qg), partly cancels with interference of gluon gluon channel, (N)LO(gg) ⇒ further reduces mass shift*

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 to measure the shift:* N.Kauer, G.Passarino, hep-ph/1206.4803
  - *ZZ* channel where interference near Higgs resonance is negligible*
  - *do it within γγ 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 may cancel to some extent*



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*

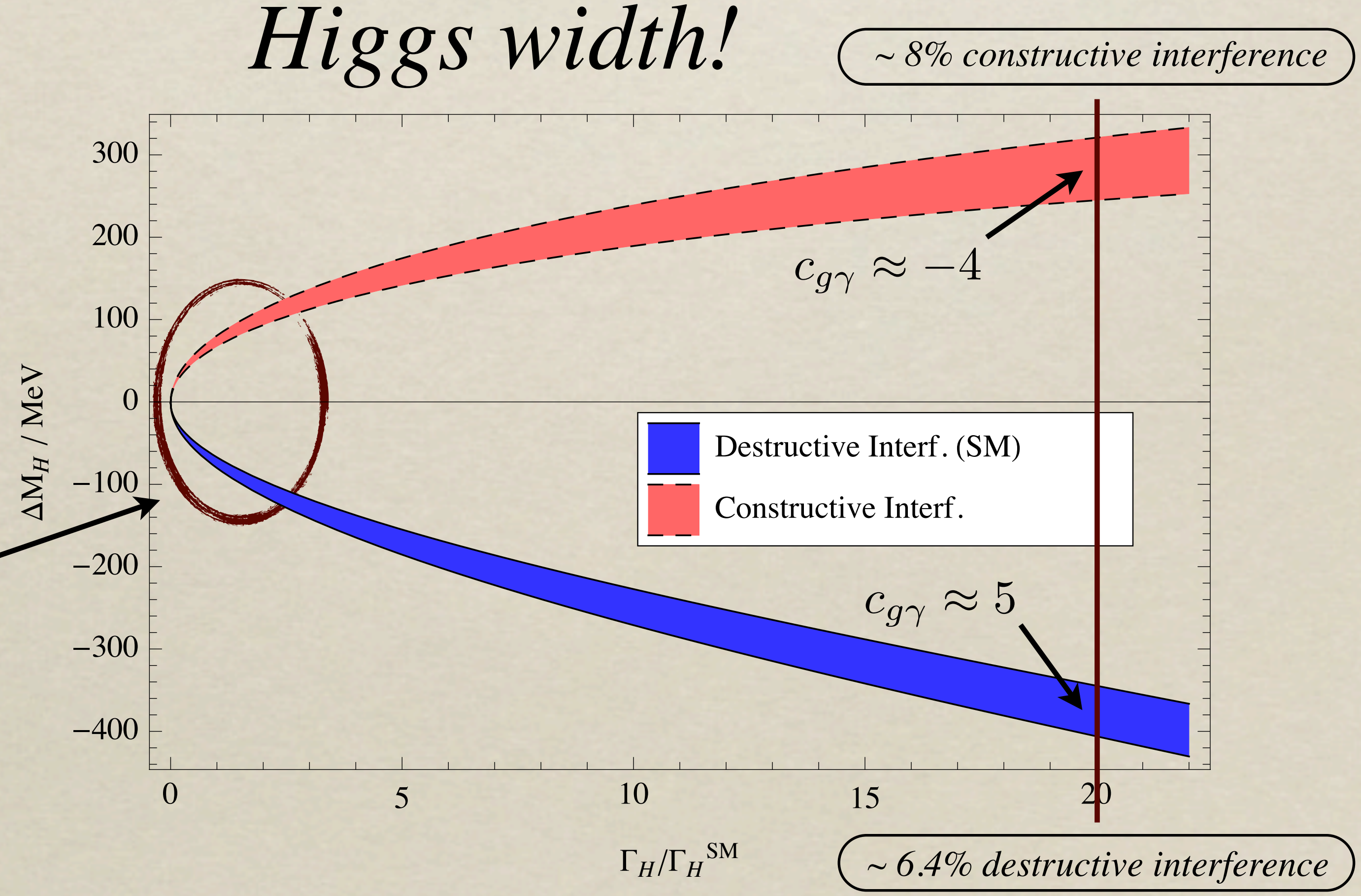
$$c_{g\gamma} = c_g c_\gamma$$

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

  - *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!*



Recap

- *The interference of Higgs signal and SM continuum background survives at NLO, allowing 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*

Other Scenarios

- *The discussion so far applies to any CP-even spin-0 particles that couples to photons and gluons similar to SM Higgs*
- *Could the observed "Higgs" be in a mixed state of CP, or even a spin-2 particle?*
  - *Interference could modify angular distribution of diphoton final states*
  - *Possible large constructive/destructive interference to signal strength*

Higgs in Mixed CP State

- *New CP-odd couplings in the effective Lagrangian*

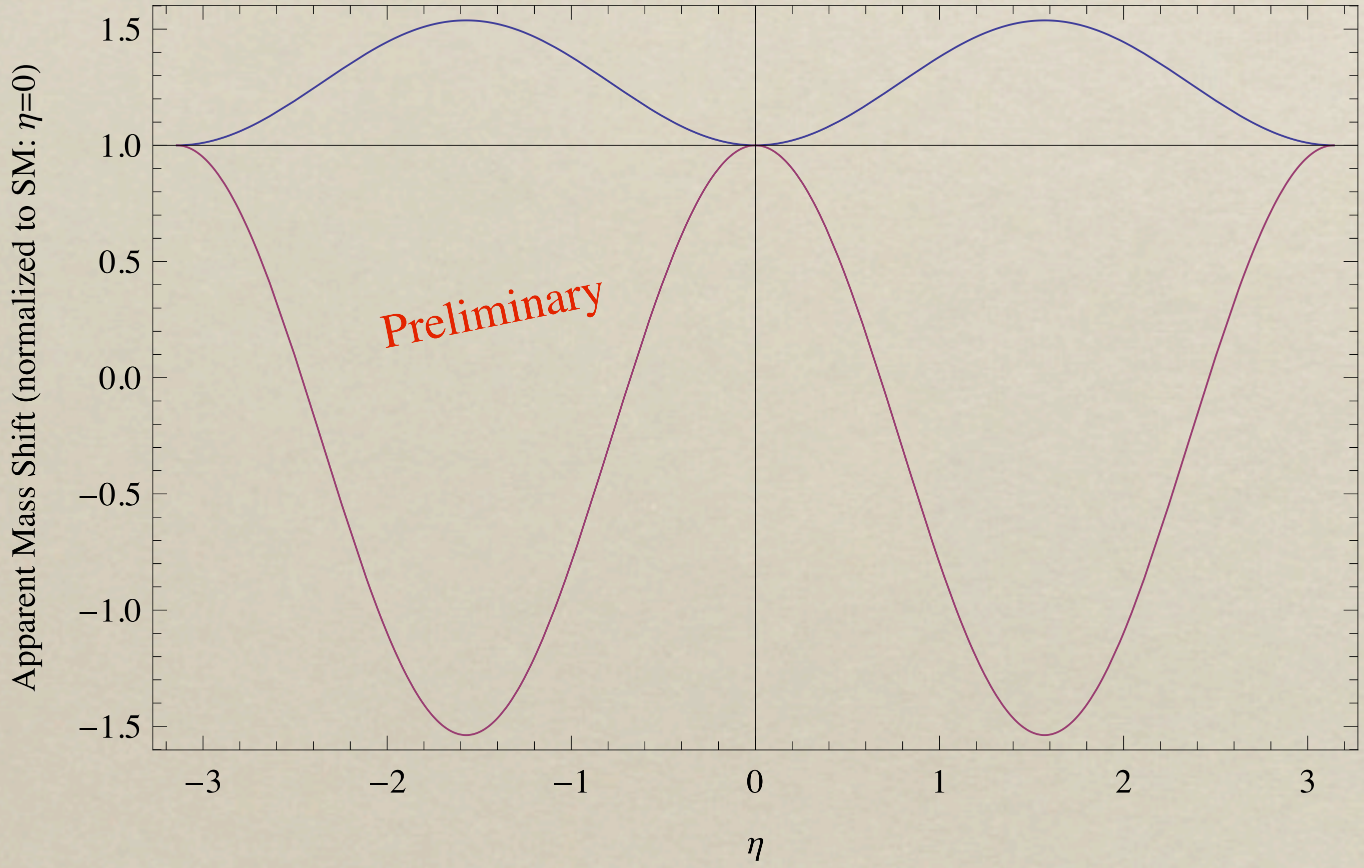
$$\mathcal{L} = -\left[\frac{\alpha_s}{8\pi}(c_g b_g G_{a,\mu\nu}G_a^{\mu\nu} + s_g d_g G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}) + \frac{\alpha}{8\pi}(c_\gamma b_\gamma F_{\mu\nu}F^{\mu\nu} + s_\gamma d_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu})\right]\frac{h}{v}$$

  - *In SM, $c_{g/\gamma}=1$ is reserved for adjusting couplings for Higgs in mixed CP state; $b_{g/\gamma}$ is given via matching from full theory; $s_{g/\gamma}d_{g/\gamma}=0$ when Higgs is a CP-even scalar*
  - *$s_{g/\gamma}$ is reserved for the same purpose as $c_{g/\gamma}$*
  - *Define $d_{g/\gamma}$ so that when we turn off original CP-even coupling ($c_{g/\gamma}b_{g/\gamma}=0$) and set $s_{g/\gamma}=1$, the total cross section of SM Higgs signal is reproduced $\Rightarrow$ $d_{g/\gamma} = b_{g/\gamma}$ at LO*

Higgs in CP Mixed State

- *To keep constant signal yield, it's not hard to find the solution: $c_{g/\gamma}^2+s_{g/\gamma}^2=1$, naturally parametrized as $c_{g/\gamma}, s_{g/\gamma} = \cos(\eta_{g/\gamma}), \sin(\eta_{g/\gamma})$*
  - *If we treat the two CP phases (η_g,η_γ) independently, the interference could change signs, resulting in positive mass shift*
  - *The mass shift is roughly 1.5 times stronger in pure CP-odd case compared to CP-even case at LO, though CP-odd case strongly disfavored experimentally*

pure CP-odd: $\eta_{g,\gamma} = \pm\frac{\pi}{2}$



- *NLO effect is hard to tell (depending on the full theory giving rise to the CP-odd couplings) but is expected to increase signal and interference both as in the SM case*

$\eta = \eta_g = \eta_\gamma$

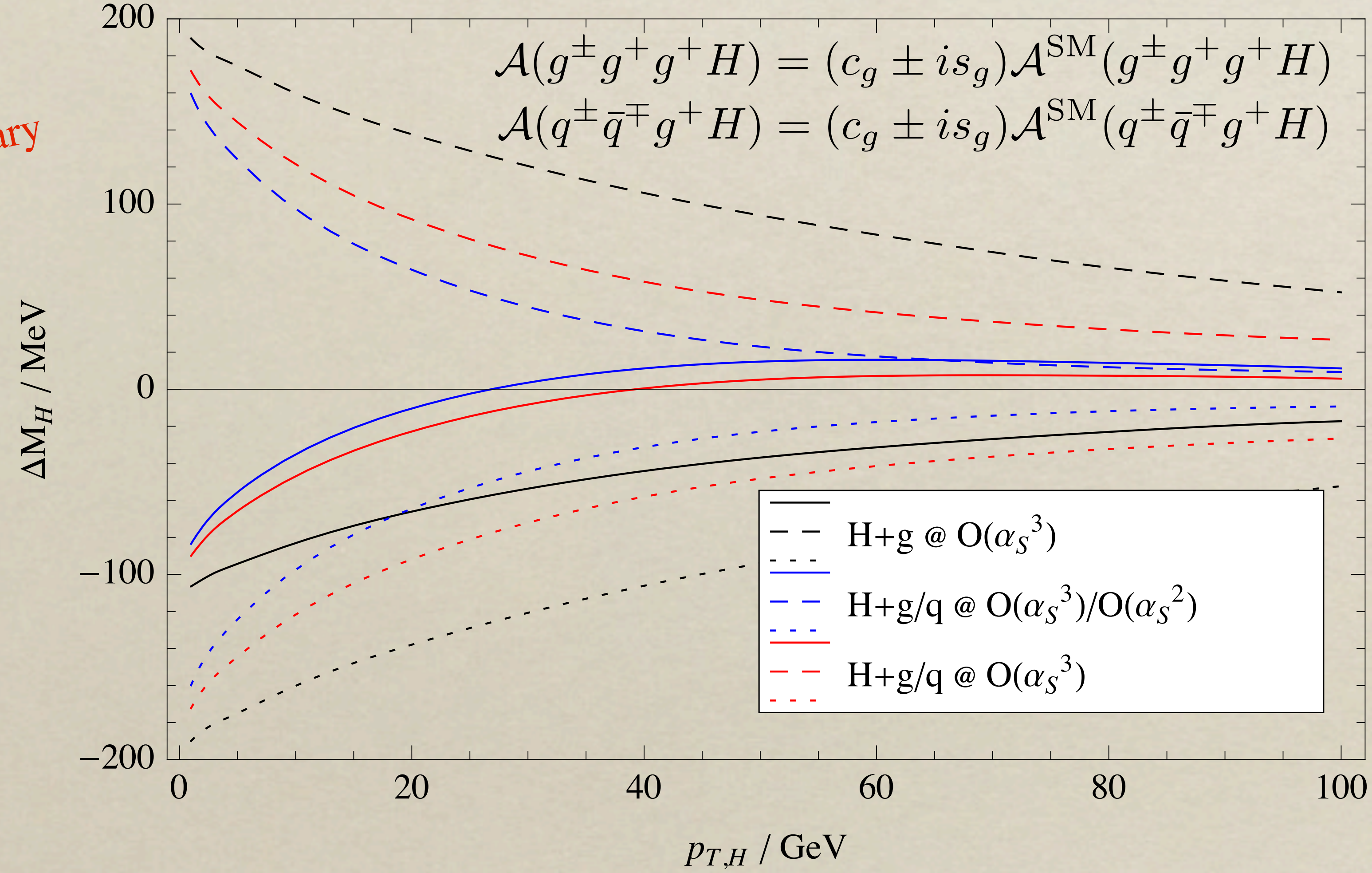
$\eta = \eta_g = -\eta_\gamma$

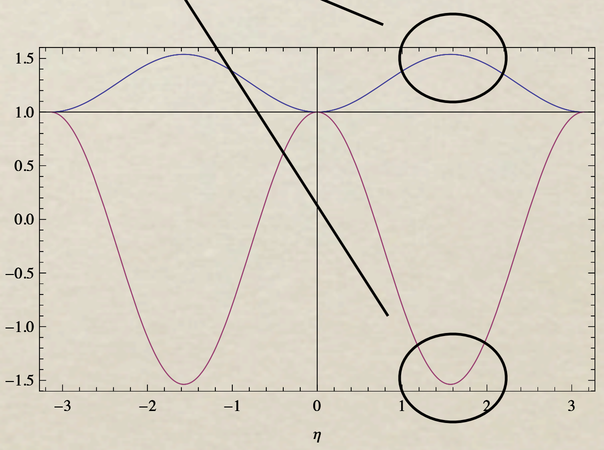
$$\mathcal{A}(g^\pm g^\pm H) = (c_g \pm i s_g)\mathcal{A}^{\rm SM}(g^\pm g^\pm H)$$
$$\mathcal{A}(\gamma^\pm \gamma^\pm H) = (c_\gamma \pm i s_\gamma)\mathcal{A}^{\rm SM}(\gamma^\pm \gamma^\pm H)$$

Higgs with Finite pT

- *The mass shift dependence of finite pT as CP phases vary has similar behavior to the zero pT case*
  - *solid line is for SM; dotted line is for $c_{g/\gamma}=0$, $s_g=s_\gamma=1$; dashed line is for $c_{g/\gamma}=0$, $s_g=-s_\gamma=1$*
  - *mass shift no longer crosses 0 in pure CP-odd case*

Preliminary





tree level analysis only

Higgs with 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*
  - *Direct coupling of H to quarks not included as it's small for graviton-like case*

Signal vs. Interference

Signal — *Interference - imaginary part*

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

Interference - real part

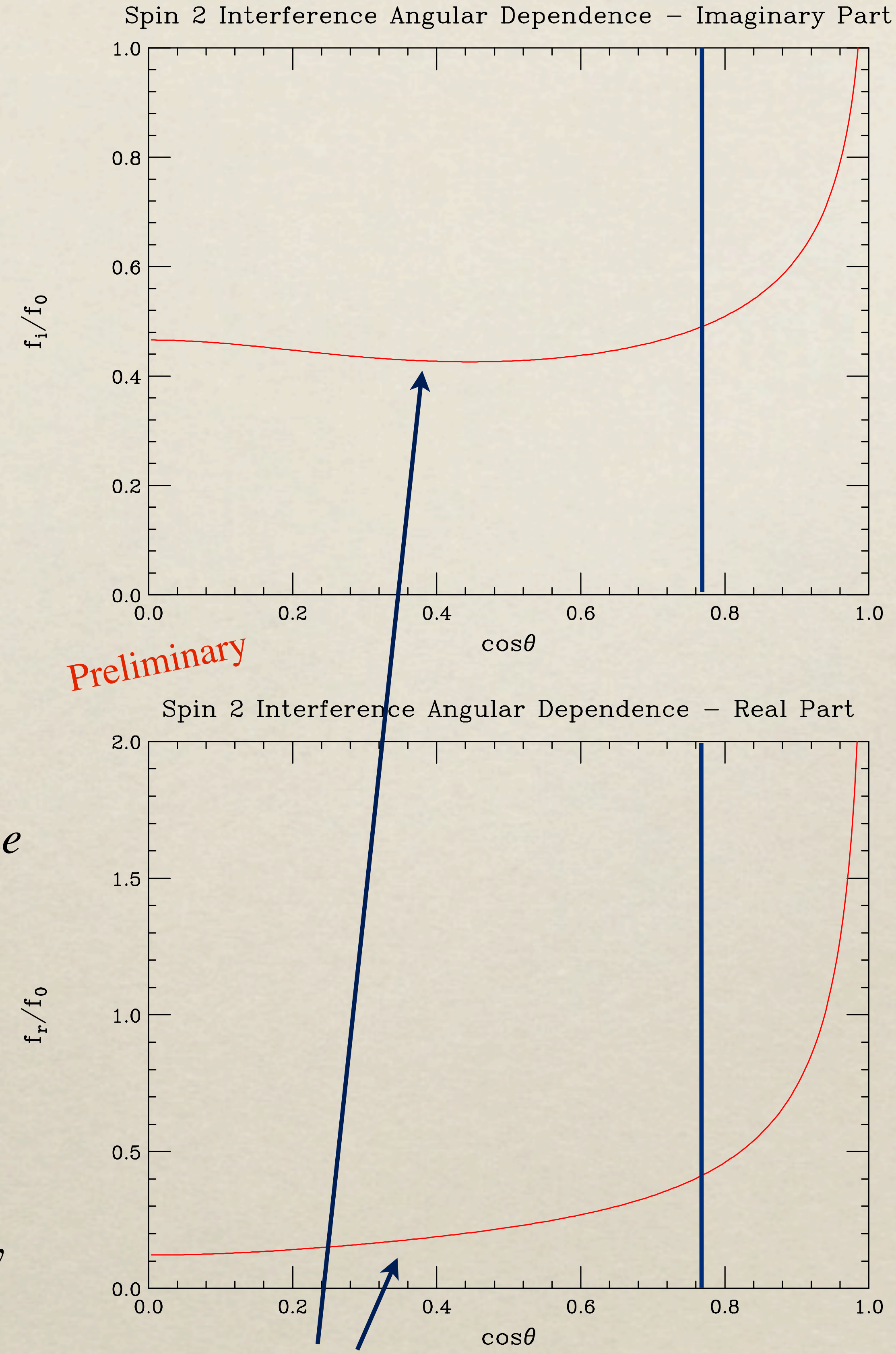
$$+\xi f_r(c)\frac{\hat{s}-M^2}{(\hat{s}-M^2)^2+M^2\Gamma^2}, \qquad c=\cos\theta, \quad \xi=\frac{11}{72}G_{g\gamma}\alpha\alpha_s$$

- *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 (40 GeV) limits photon to central region where interference and signal has relatively similar angular dependence*

$$\cos\theta_{max} = \sqrt{1-2(p_T^{cut}/M_{\gamma\gamma})^2} \xrightarrow{p_T^{cut}=40\text{GeV}} 0.77$$

        - *signal-only angular distribution analysis largely unaffected by interference contribution*

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

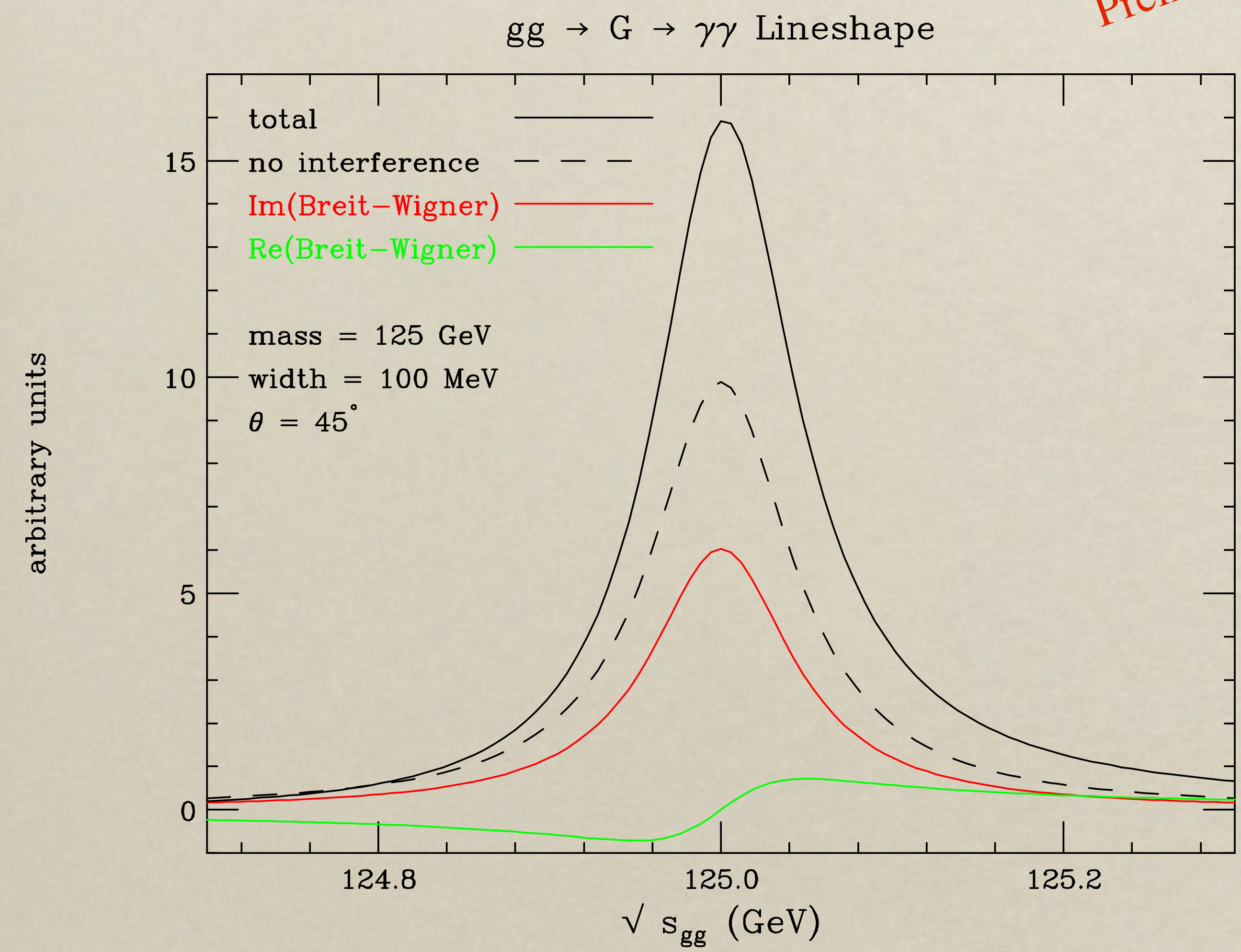


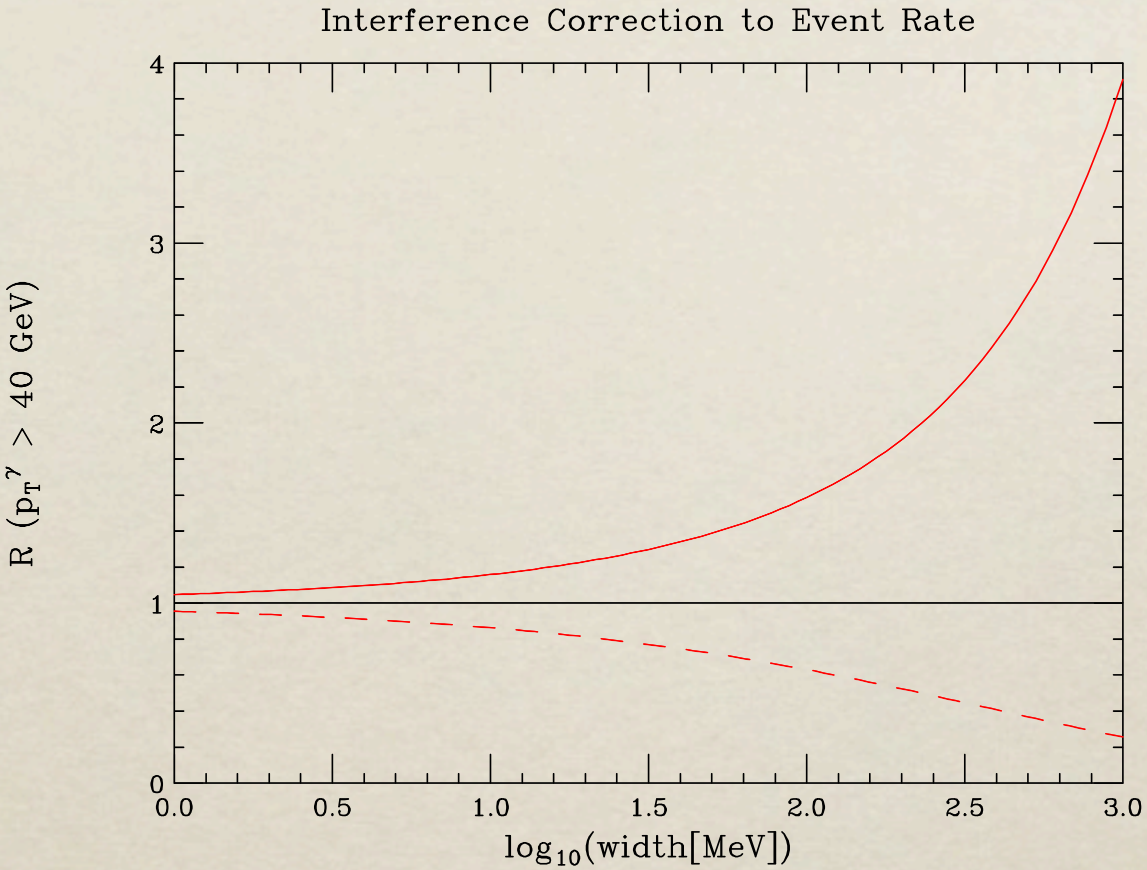
almost flat profile for small scattering angle

Interference on Signal Yields (Spin-2)

- *Strong constructive/ destructive interference at large width because imaginary part interference starts at LO*

Preliminary





- *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 angular correlation analysis*
  - *Higher order correction with resummation helpful for future precision studies*
- *What role interference plays in Higgs production via vector boson fusion?*
  - *most likely small but needs to be examined*

Conclusion

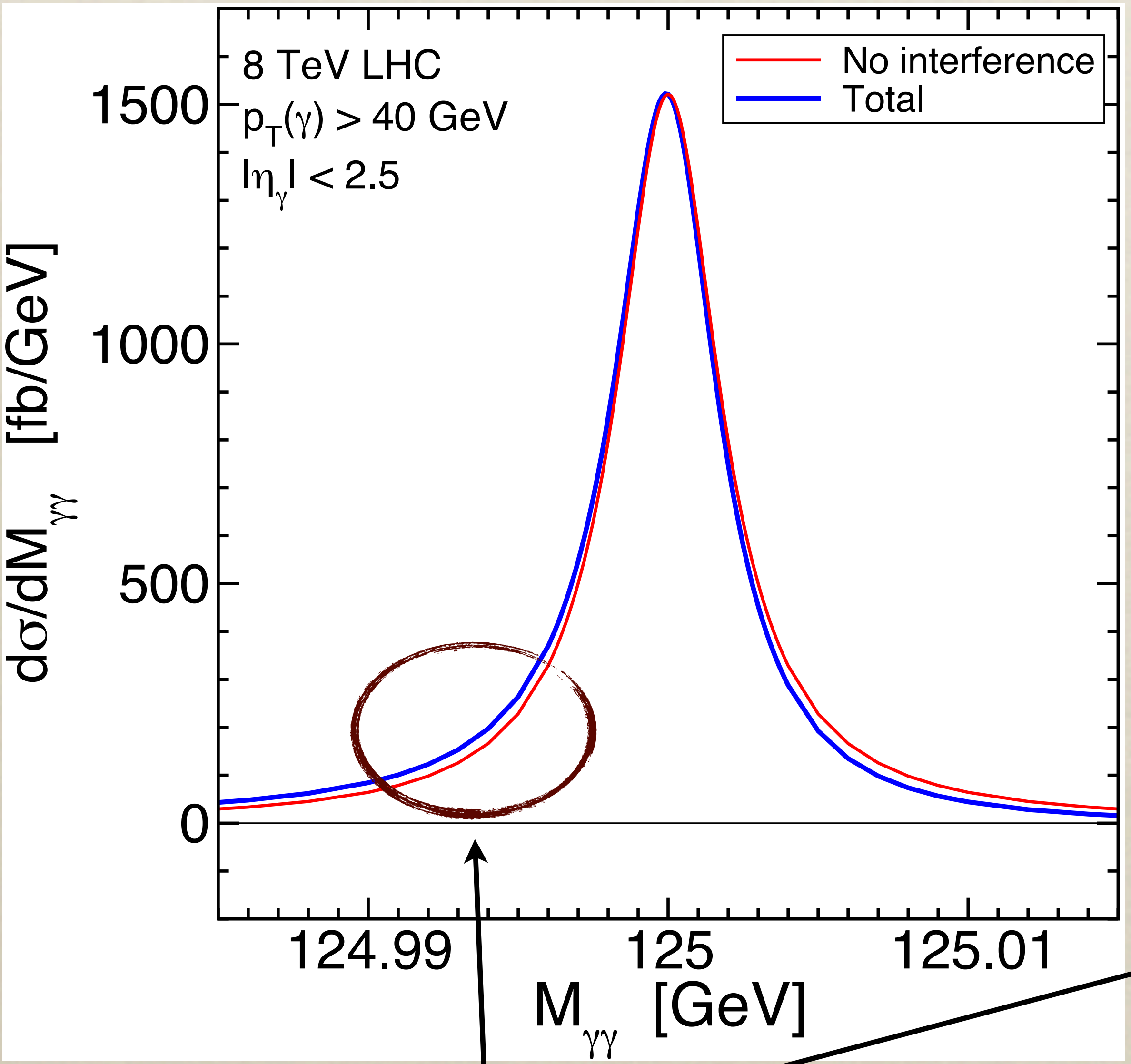
- *The interference in Higgs diphoton decay channel provides additional degree of freedom to constrain/measure Higgs width*
- *Interference can also be used to probe other properties of Higgs: spin, CP ...*

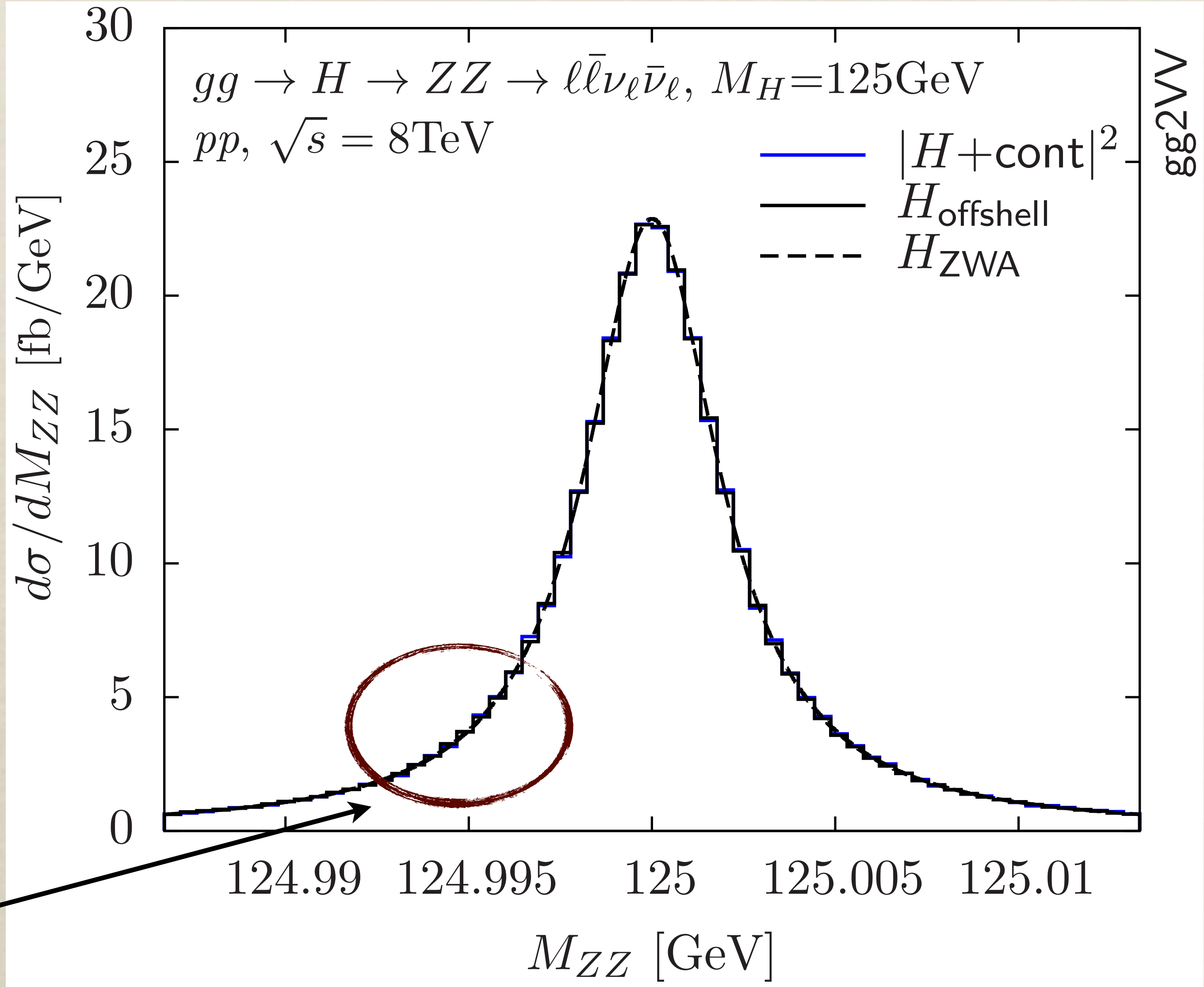
Backup slides

Interference in ZZ and γγ

S.Martin, hep-ph/1303.3342

N.Kauer, G.Passarino, hep-ph/1206.4803





interference in ZZ is very small

The mass measurement can be approximated by a least square fit of the mass peak, which can be shown via likelihood analysis by assuming a relatively constant and well-modeled background in the mass range of consideration