Bounding Higgs Width Through Interferometry

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

Ye Li

DPF 2013 Meeting
University of California, Santa Cruz
Aug 16, 2013

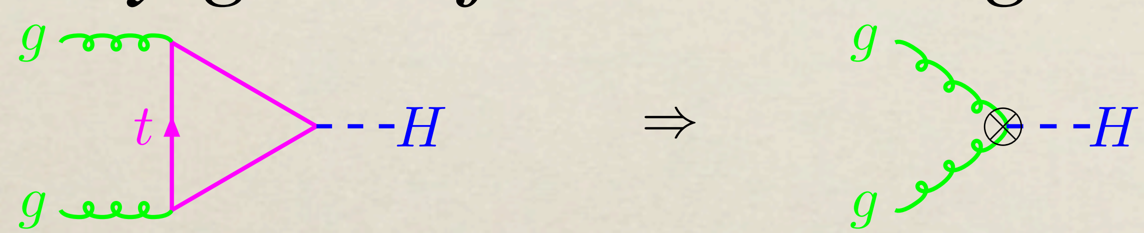
UC SANTA CRUZ

Outline

- *Interference in* $gg \to H \to \gamma\gamma$
- *Real part interference: mass shift*
- *NLO corrections to interference*
- *Bounding* Γ_H *using mass shift*
- *Conclusion*

Higgs Production

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



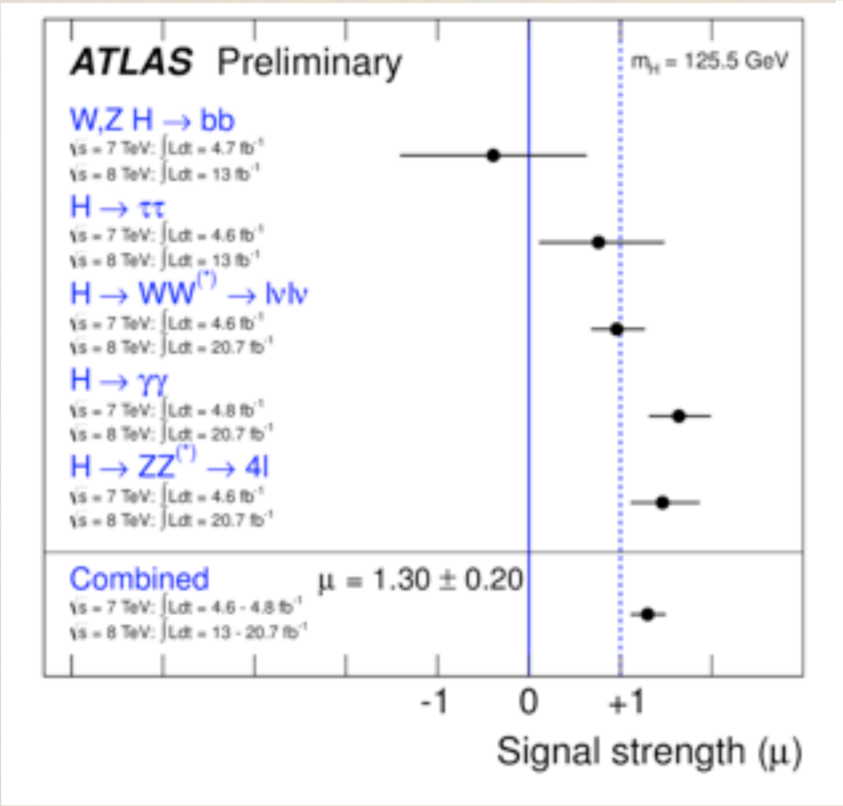
- *To make higher order correction feasible, approximate top quark loop by effective ggH vertex*
- *Similarly, photon couples to Higgs through top quark and W boson loop, can also be approximated by effective $\gamma\gamma H$ vertex*

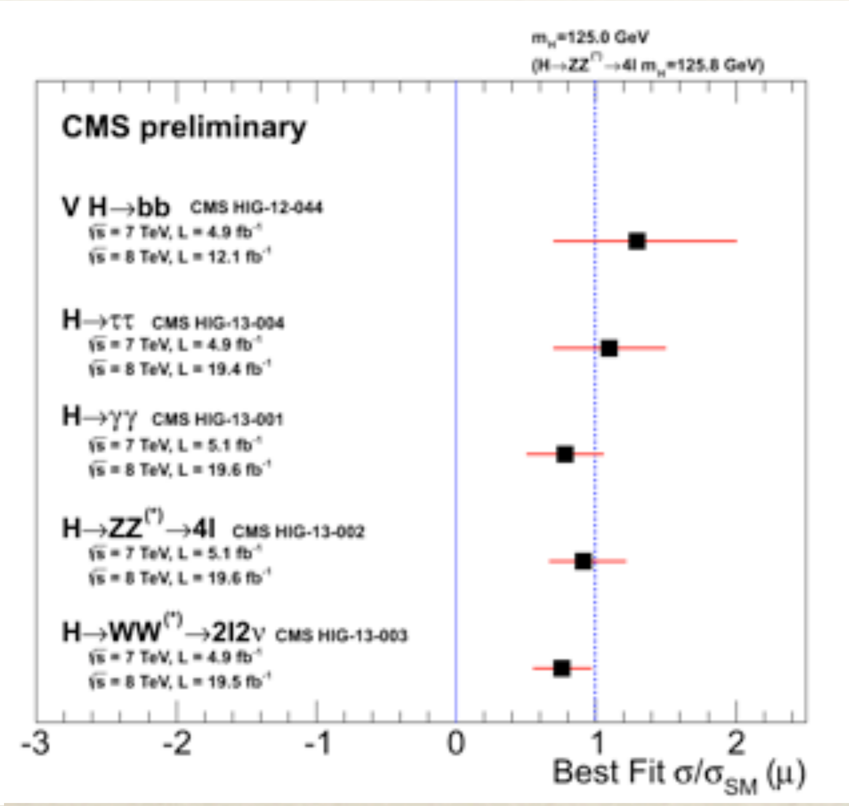
$\mathrm{SM:}\ \ b_{g,\gamma} = \frac{2}{3}, \frac{47}{9}$ at LO in heavy top/W limit

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 $m_H \sim 125$GeV, 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*

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

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

- *Higgs signal appears as resonance in diphoton invariant mass $M_{\gamma\gamma}$ spectrum*
- *Finite detector resolution make direct measurement on Higgs width impossible*
- *The only observable: signal strength in narrow width approximation*

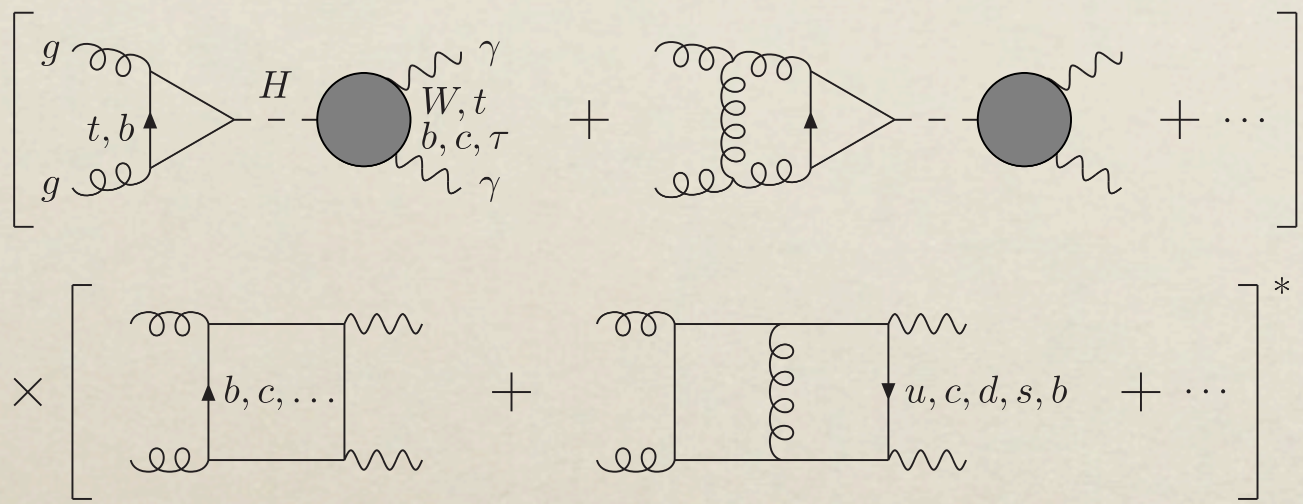
$S \sim |\mathcal{A}_{gg\to H}\mathcal{A}_{\gamma\gamma\to H}|^2$

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

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*

Interference



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

- *Need to examine the width dependence of the interference*
- *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 contribution of the interference term: suppressed by small Higgs width in size comparing to the 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*

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

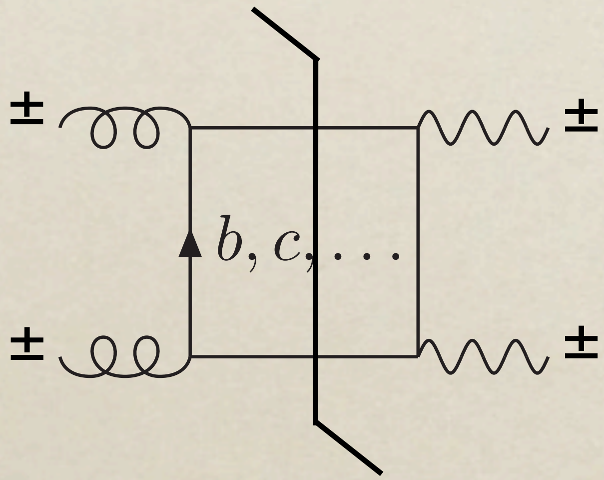
$$\sigma^{int} = \int dM_{\gamma\gamma} \frac{(M^2_{\gamma\gamma} - m^2_H)R + m_H \Gamma_H I}{(M^2_{\gamma\gamma} - m^2_H)^2 + m^2_H \Gamma^2_H} \sim c_g c_\gamma$$

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 contribution depending on the relative phase between signal and background*

Imaginary part of Interference

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



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

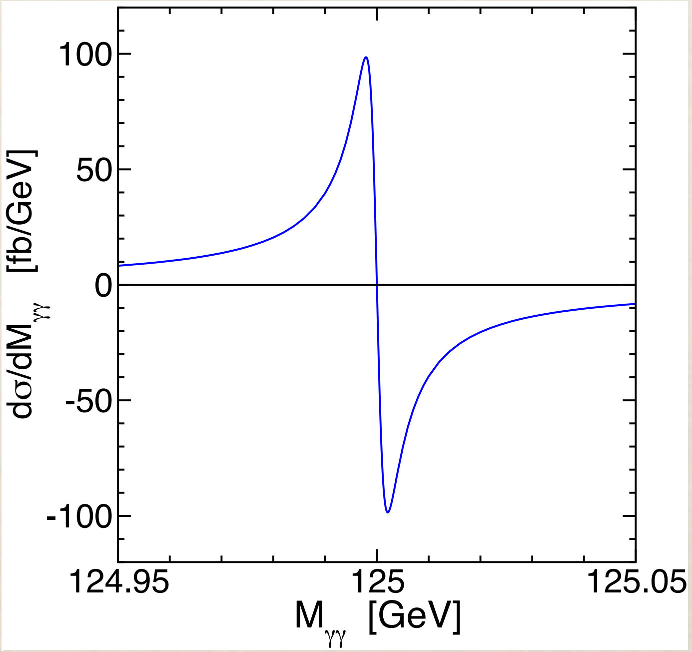
- *The full gg→H→γγ signal amplitude is mainly real due to the dominant contribution from heavy top and W loops; contribution from light quark loops is suppressed by Yukawa couplings*

- *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*
- *Major imaginary part of SM background starts at 2-loop, leading to 1-2% destructive interference*
- *Too small an effect to see ...*

Theoretical uncertainty on signal~15%

LO Mass Shift

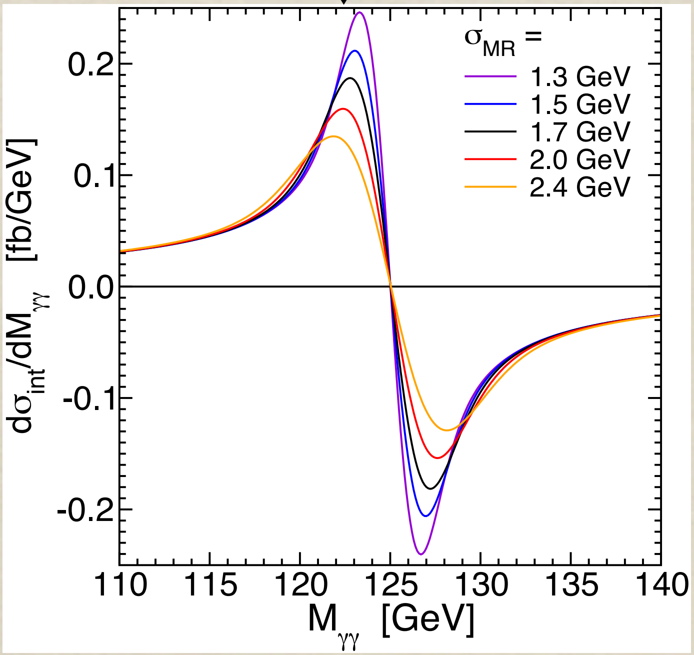
Interference only (LO)



- *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*

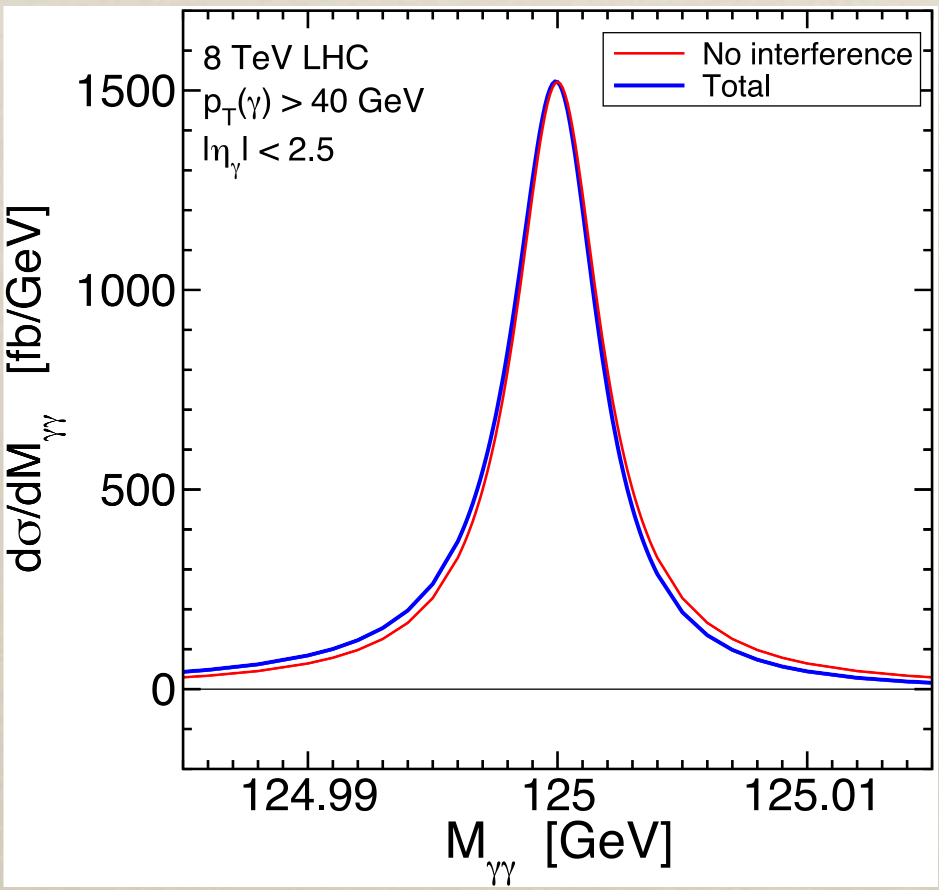
S.Martin, hep-ph/1208.1533

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

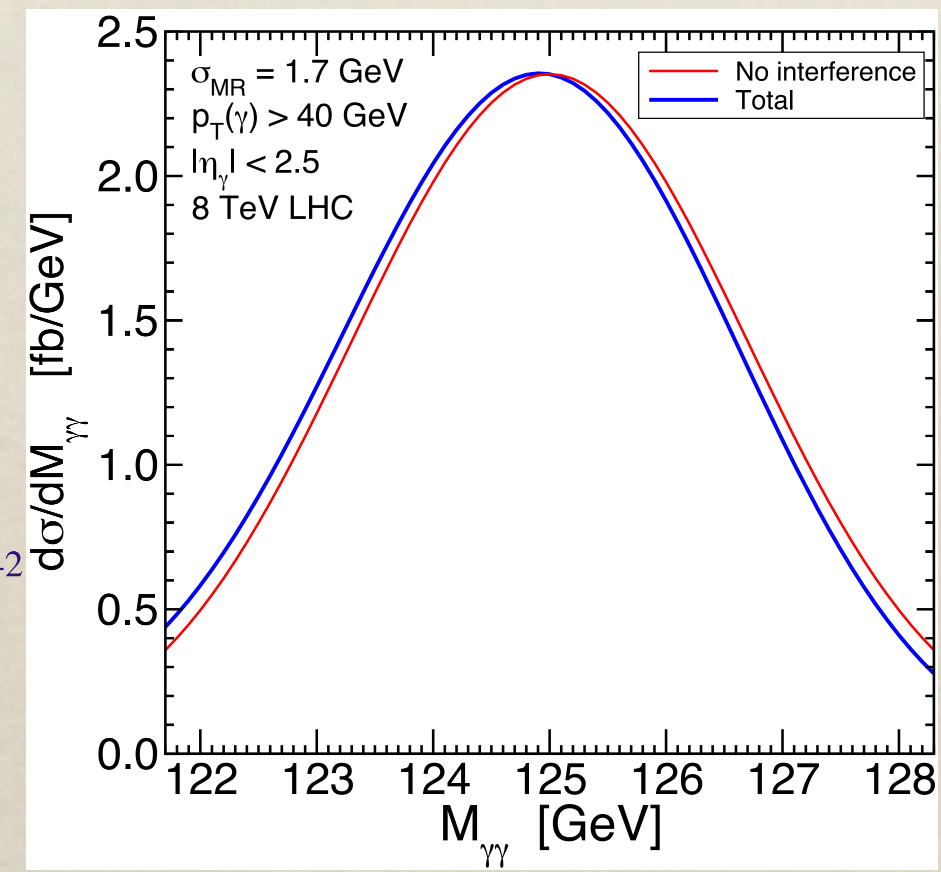


LO Mass Shift

illustration of how interference changes the diphoton invariant mass spectrum



S.Martin, hep-ph/1303.3342



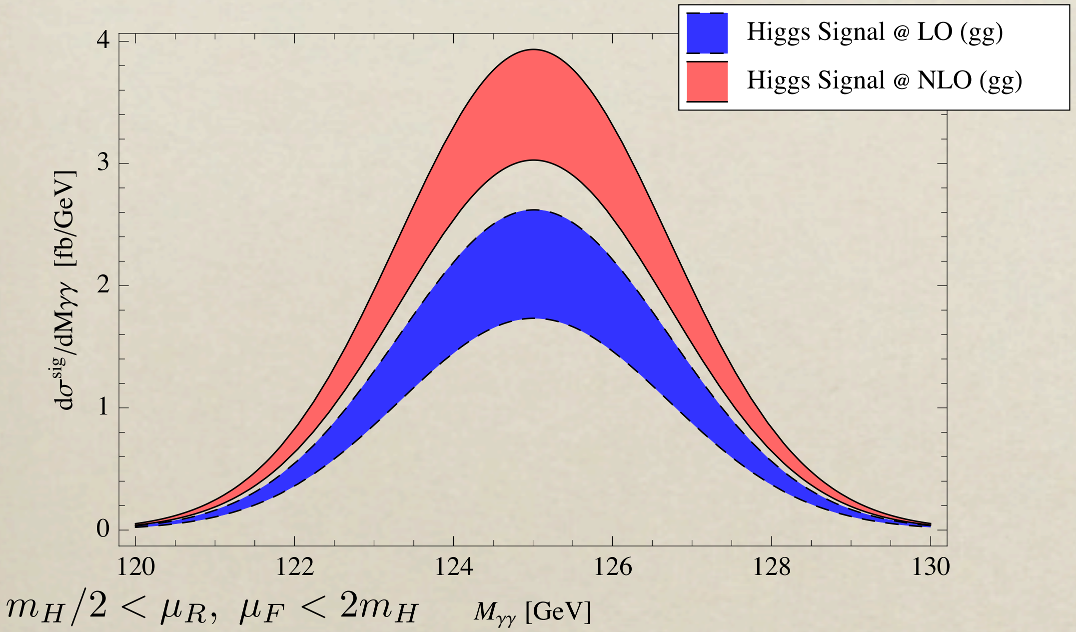
diphoton spectrum in ideal detector

spectrum with detector mass resolution of 1.7 GeV

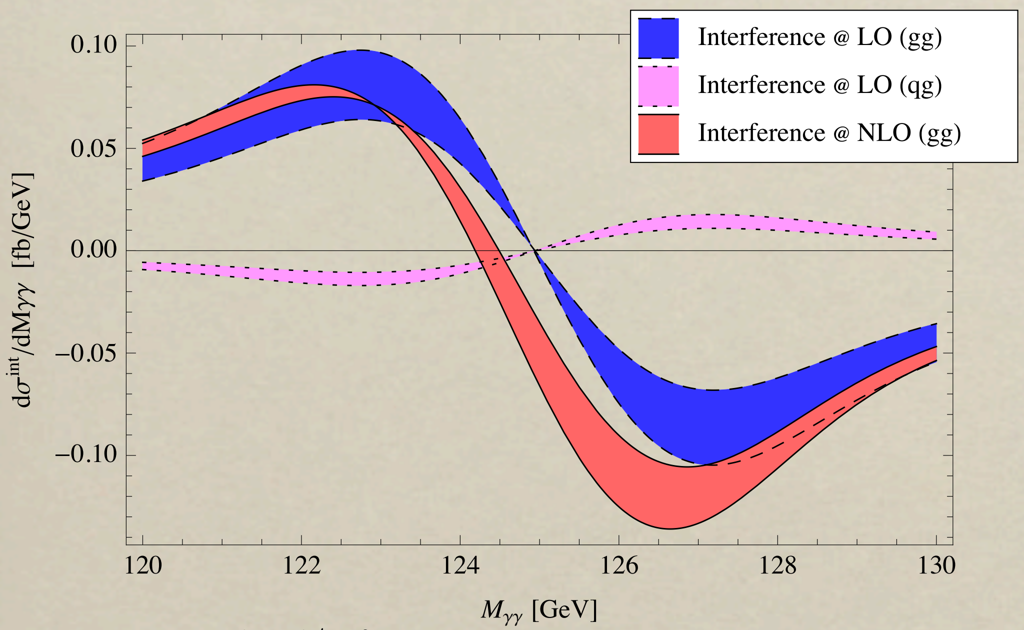
NLO QCD Correction

LHC @ 8 TeV

$\sigma_{MR} = 1.7$ GeV



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



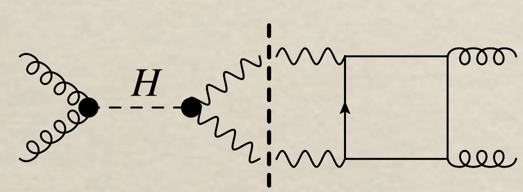
$p_{T,\gamma}^{\mathrm{hard/soft}} > 40/30$ GeV, $|\eta_\gamma| < 2.5$

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

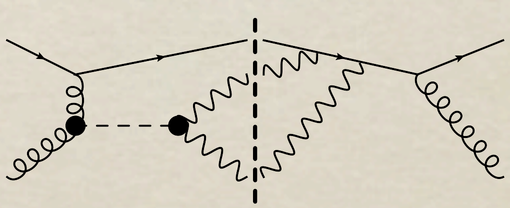
Veto jet : $p_{T,j} > 20$ GeV, $\eta_j < 3$

- *Known large K factor of Higgs production and SM background in QCD at NLO*
  - *more uncertainty when pT veto is involved*
- *Complicated K factor dependence on $M_{\gamma\gamma}$ spectrum for interference due to interplay between the two parts*
  - *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)*

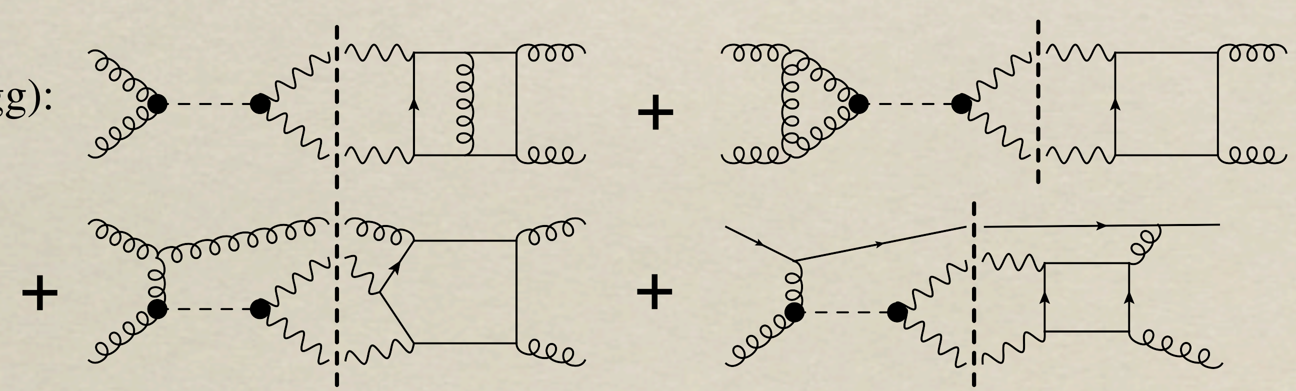
LO (gg):

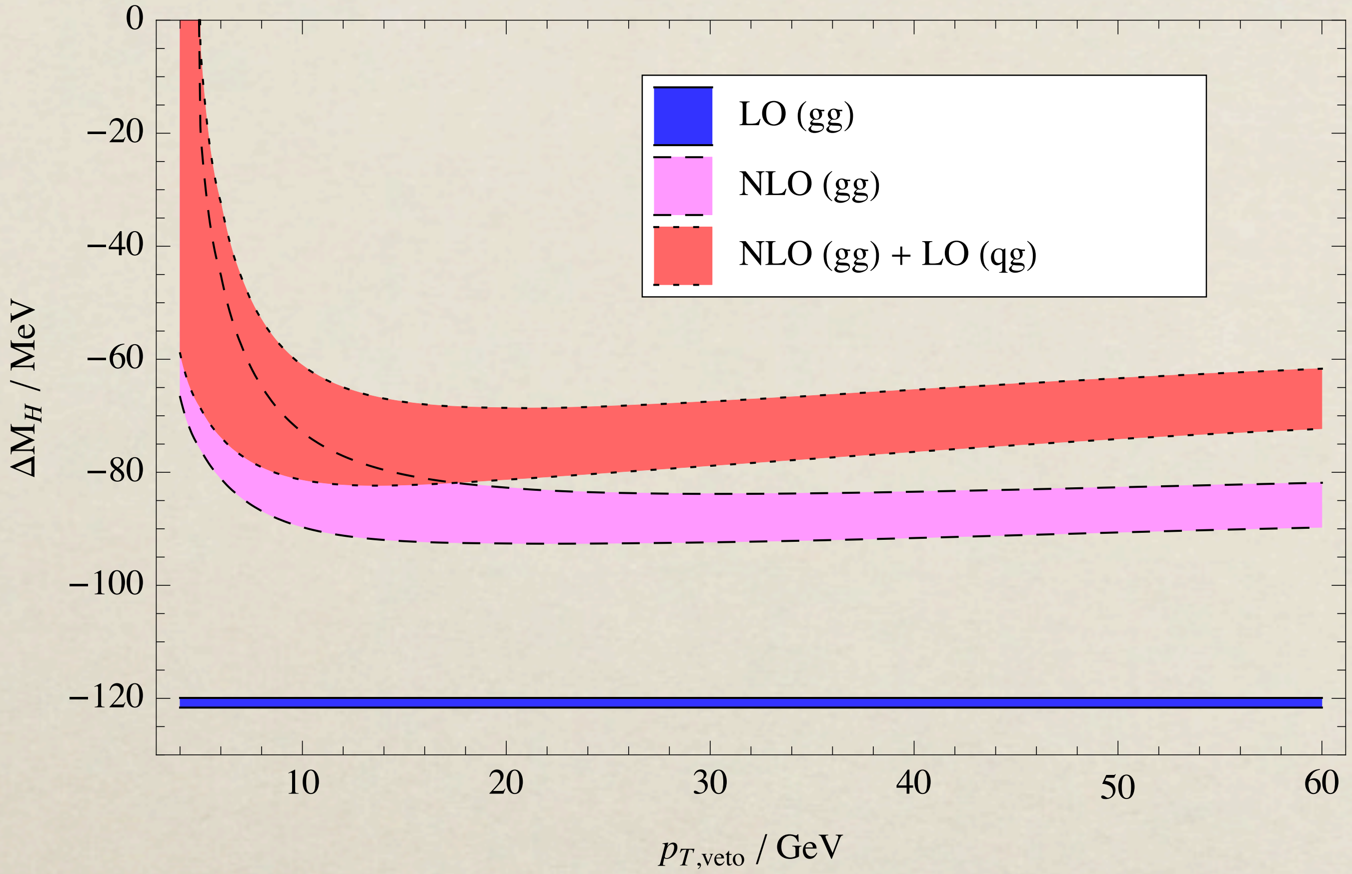


LO (qg):



NLO (gg):





- *smaller K factor compared to signal ⇒ 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*

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*

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

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

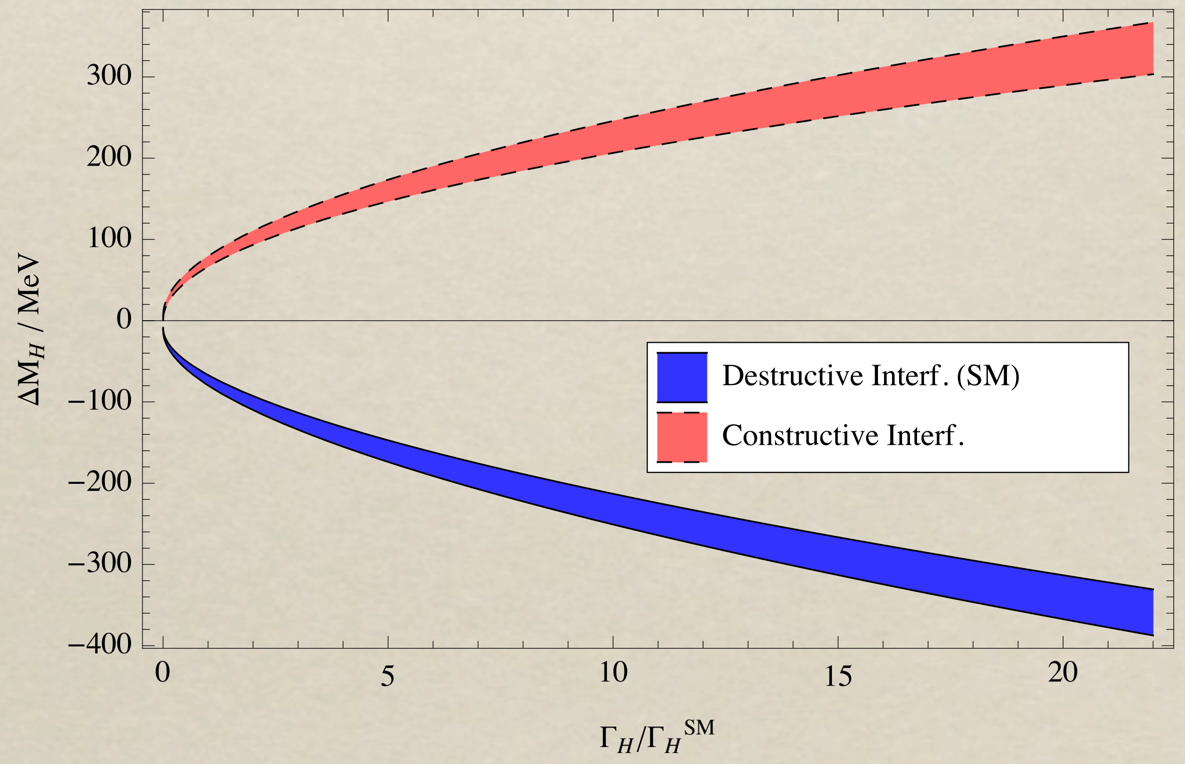
ratio of experimental signal strength to SM prediction

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

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

for $\mu_{\gamma\gamma} = 1$

- *In case NP flips the sign of Higgs amplitude ⇒ Constructive Interference*
- *Complement to ILC in constraining Higgs width!*



Probing Mass Shift

- *Need a reference channel to measure the shift:*

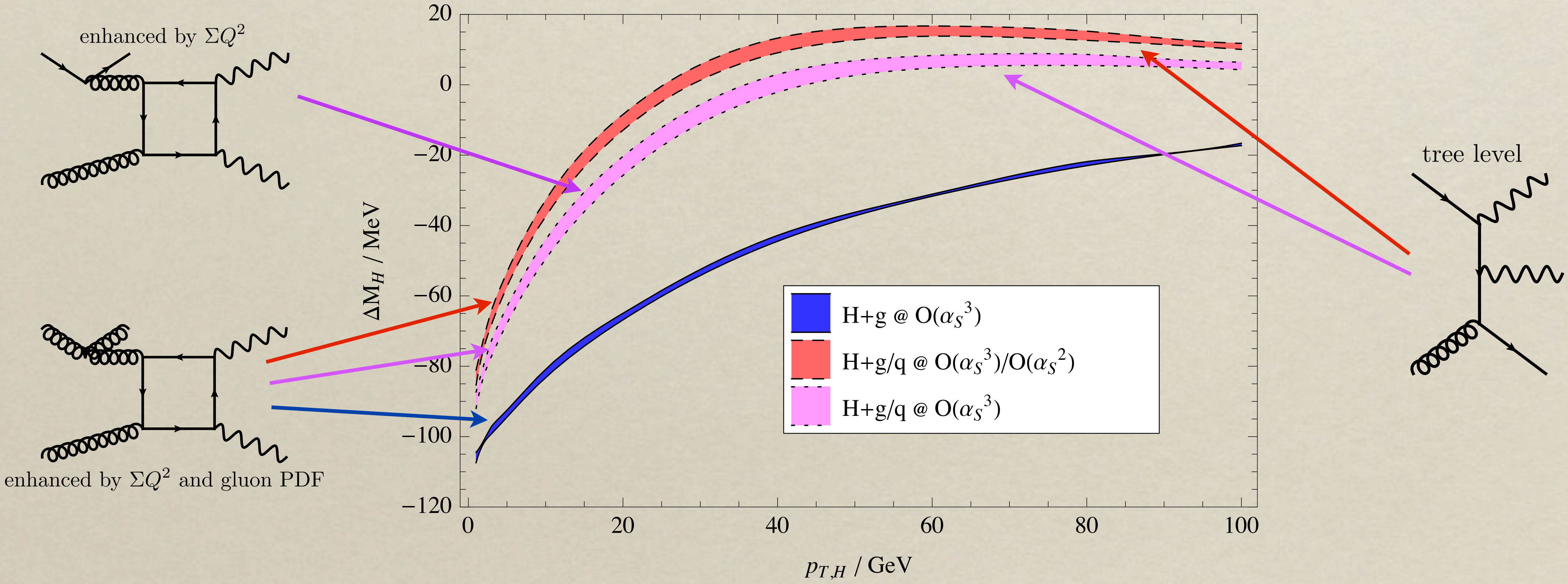
  N.Kauer, G.Passarino, hep-ph/1206.4803

  - *ZZ* channel where interference near Higgs resonance is negligible*
  - *Possible large systematic errors as current ATLAS and CMS results incompatible*

$$
\begin{aligned}
m_H^{\gamma\gamma} - m_H^{ZZ} &= +2.3^{+0.6}_{-0.7} \pm 0.6 \text{ GeV (ATLAS)} \\
&= -0.4 \pm 0.7 \pm 0.6 \text{ GeV (CMS)},
\end{aligned}
$$

S.Martin, hep-ph/1303.3342

- *Cancellation between qg and gg channels results in strong dependence on Higgs pT ⇒ virtually no mass shift on high pT events*



Constraining the Width

- *Potentially able to measure mass shift using two Higgs pT bins*
    - *Better choice because experimental systematic uncertainty may cancel to some extent; still limited by statistics at present*
    - *At high luminosity LHC with 3 ab^{-1} data, statistical error on mass shift should drop to below 50 MeV; while the extrapolation of systematic error is somewhat uncertain but should result in a total error of 100 MeV or less, corresponding to a bound of Higgs width of around 15 times that of SM value (4 MeV) at 95% C.L.*

Conclusion

- *Part of Higgs signal and background interference proportional to real part of BW propagator yields potentially observable mass shift with finite detector resolution*
- *The mass shift survives at NLO in QCD, allowing possibility to study the interference experimentally, and decouple the Higgs width and coupling measurements*
- *Increasing Higgs width leads to considerably larger mass shift which can be used to bound the width*
- *Strong dependence of mass shift on finite Higgs pT provides way of probing it without reference to ZZ* decay channel*

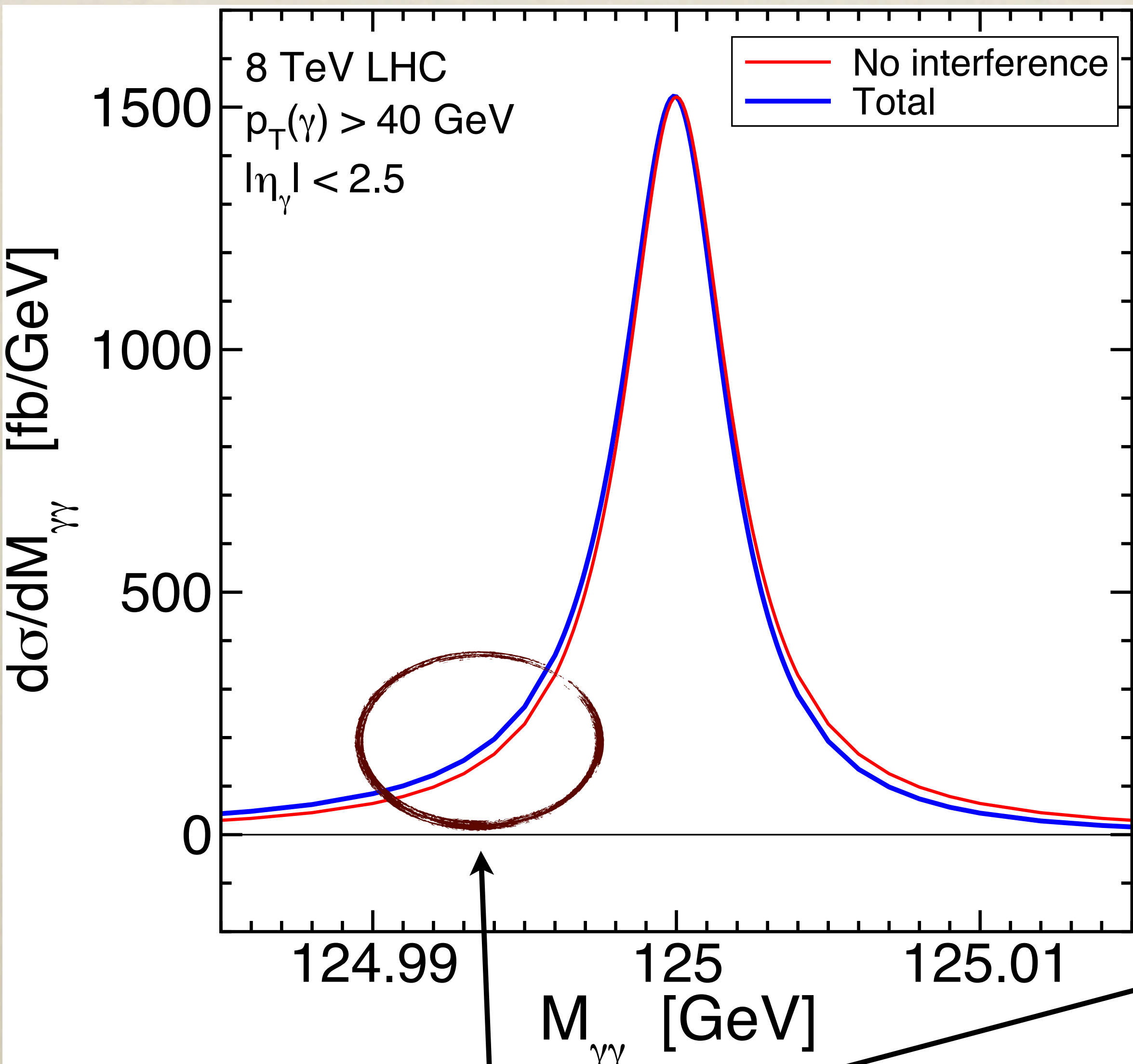
Thank you !

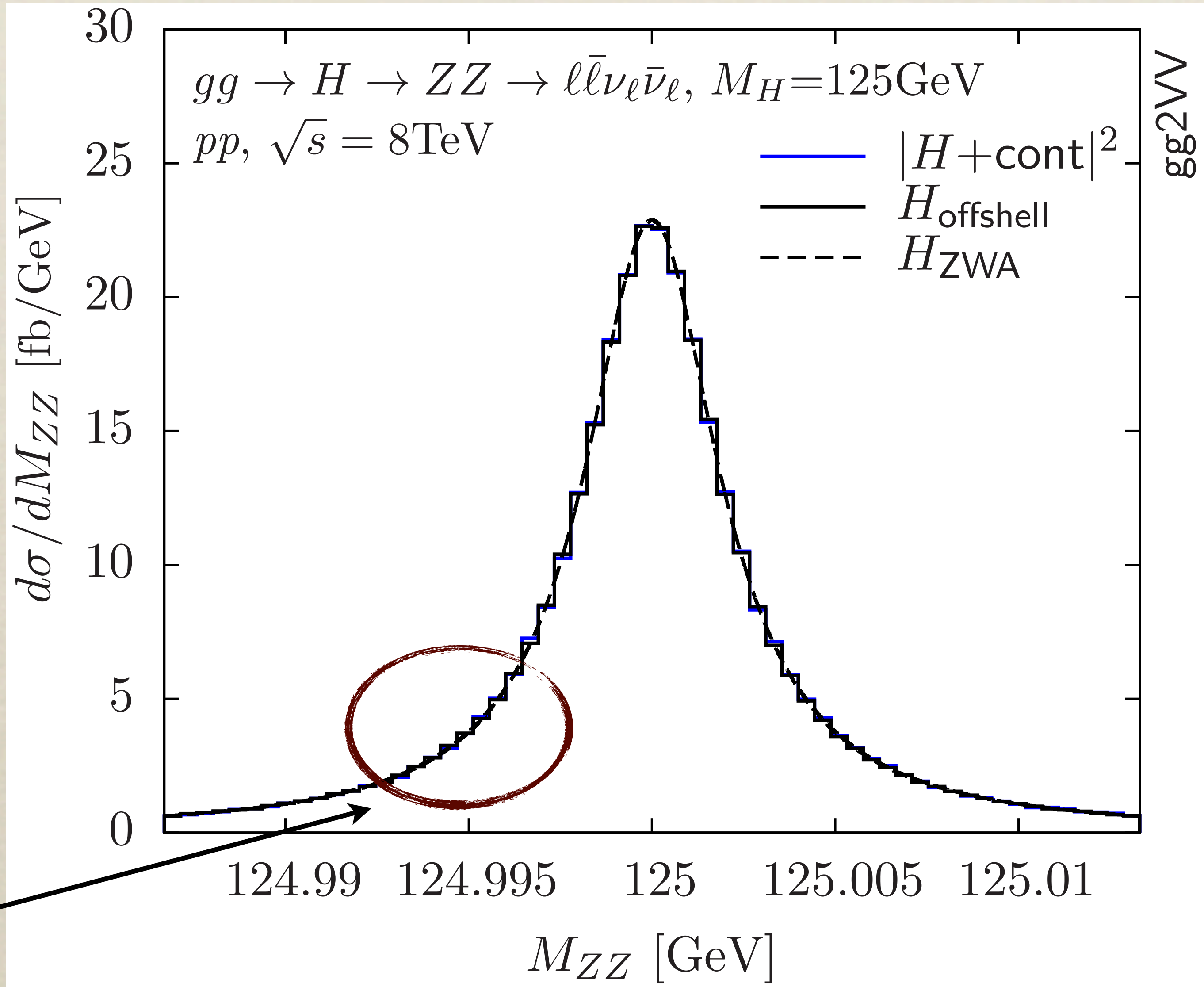
Backup slides

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

Higgs in Mixed CP State

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

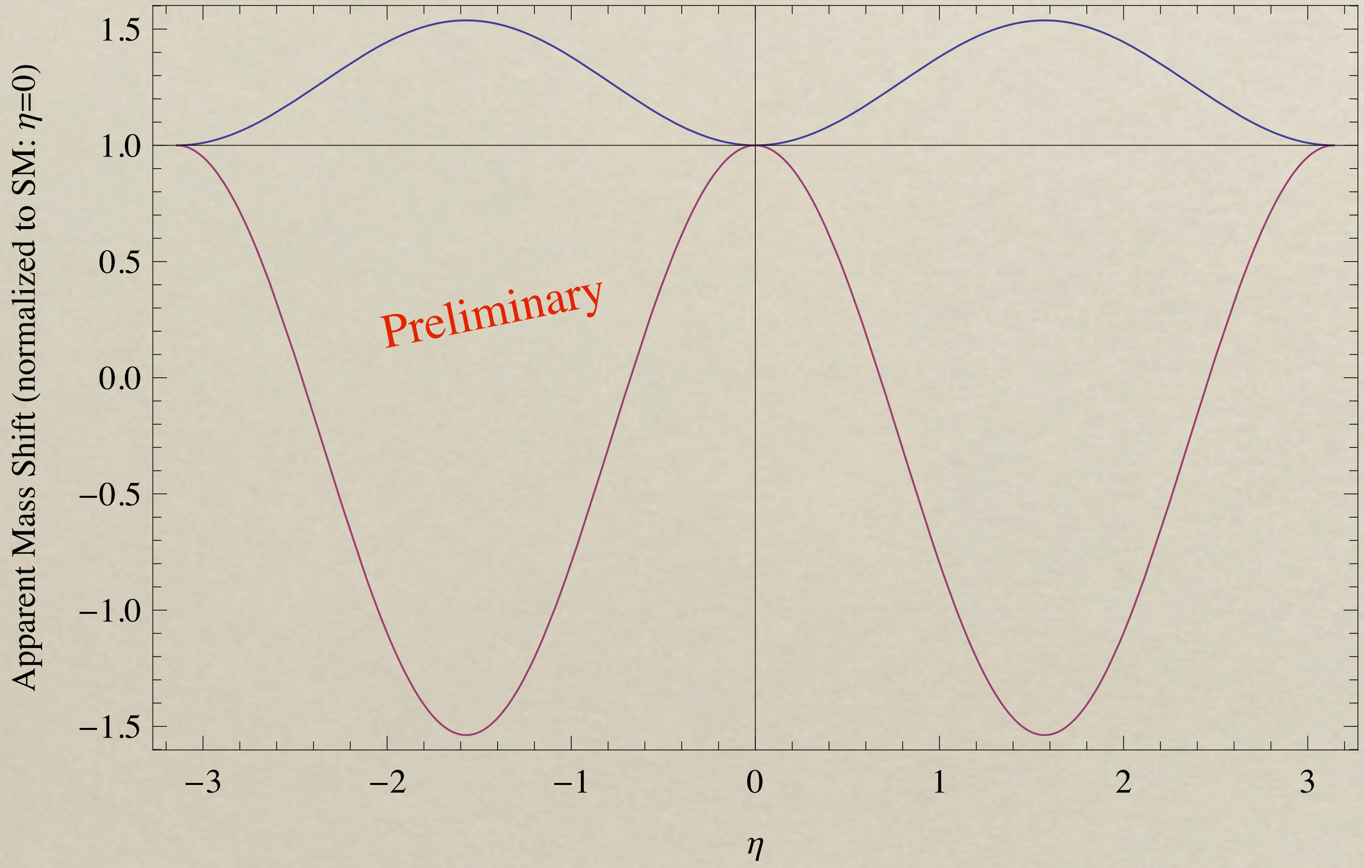
$$\mathcal{L} = -\left[\frac{\alpha_s}{8\pi}(c_g b_g G_{a,\mu\nu} G_a^{\mu\nu} + s_g d_g G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}) + \frac{\alpha}{8\pi}(c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu} + s_\gamma d_\gamma F_{\mu\nu} \tilde{F}^{\mu\nu})\right] \frac{h}{v}$$

  - *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*

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

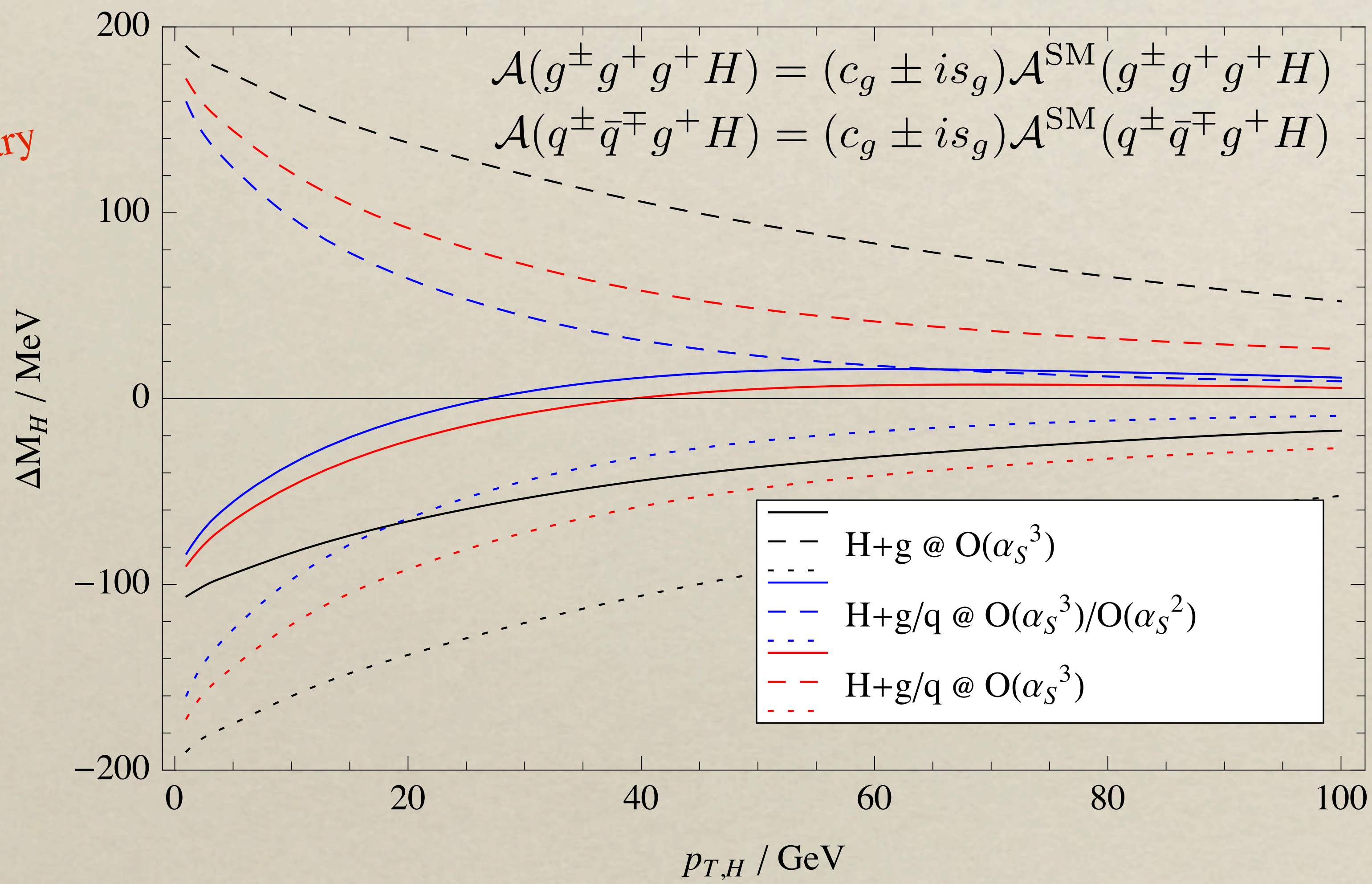
$\eta = \eta_g = -\eta_\gamma$

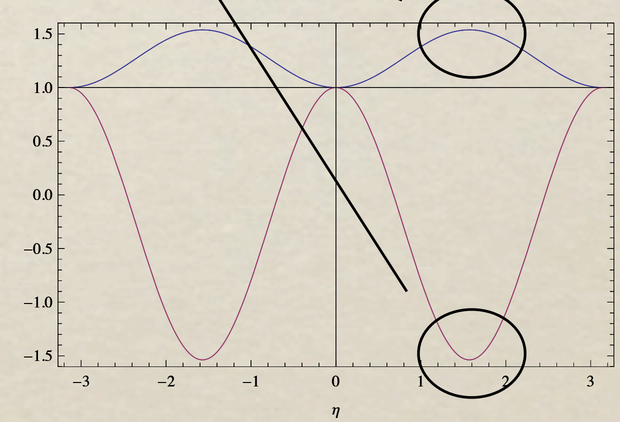
$$\mathcal{A}(g^\pm g^\pm H) = (c_g \pm i s_g)\mathcal{A}^{\rm SM}(g^\pm g^\pm H)$$
$$\mathcal{A}(\gamma^\pm \gamma^\pm H) = (c_\gamma \pm i s_\gamma)\mathcal{A}^{\rm SM}(\gamma^\pm \gamma^\pm H)$$

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; <u>dotted line</u> is for $c_{g/\gamma}=0$, $s_g=s_\gamma=1$; <u>dashed line</u> 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*

Interference - real part

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

$$c = \cos\theta$$

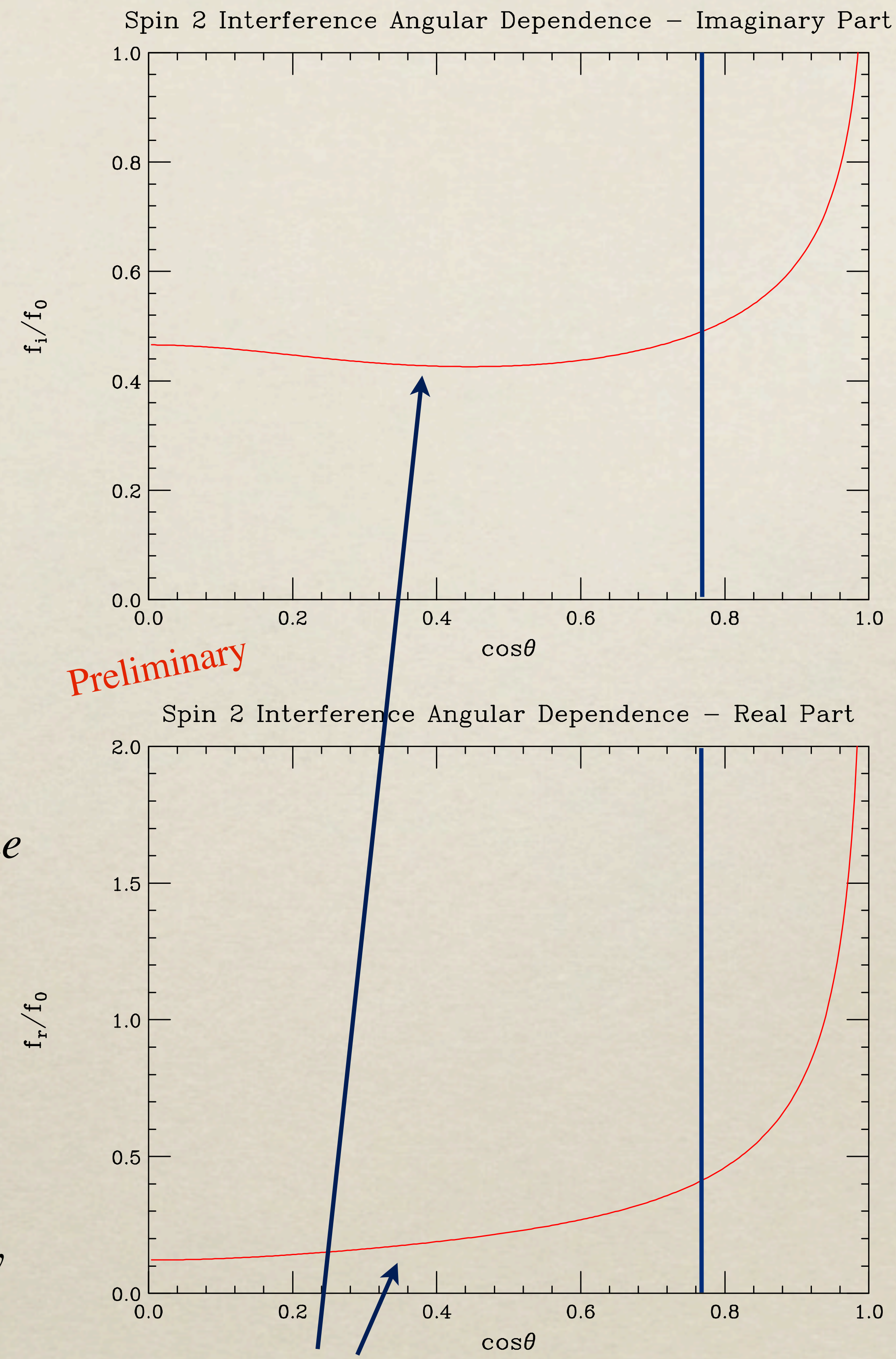
$$\xi = \frac{11}{72}G_{g\gamma}\alpha\alpha_s$$

- *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*

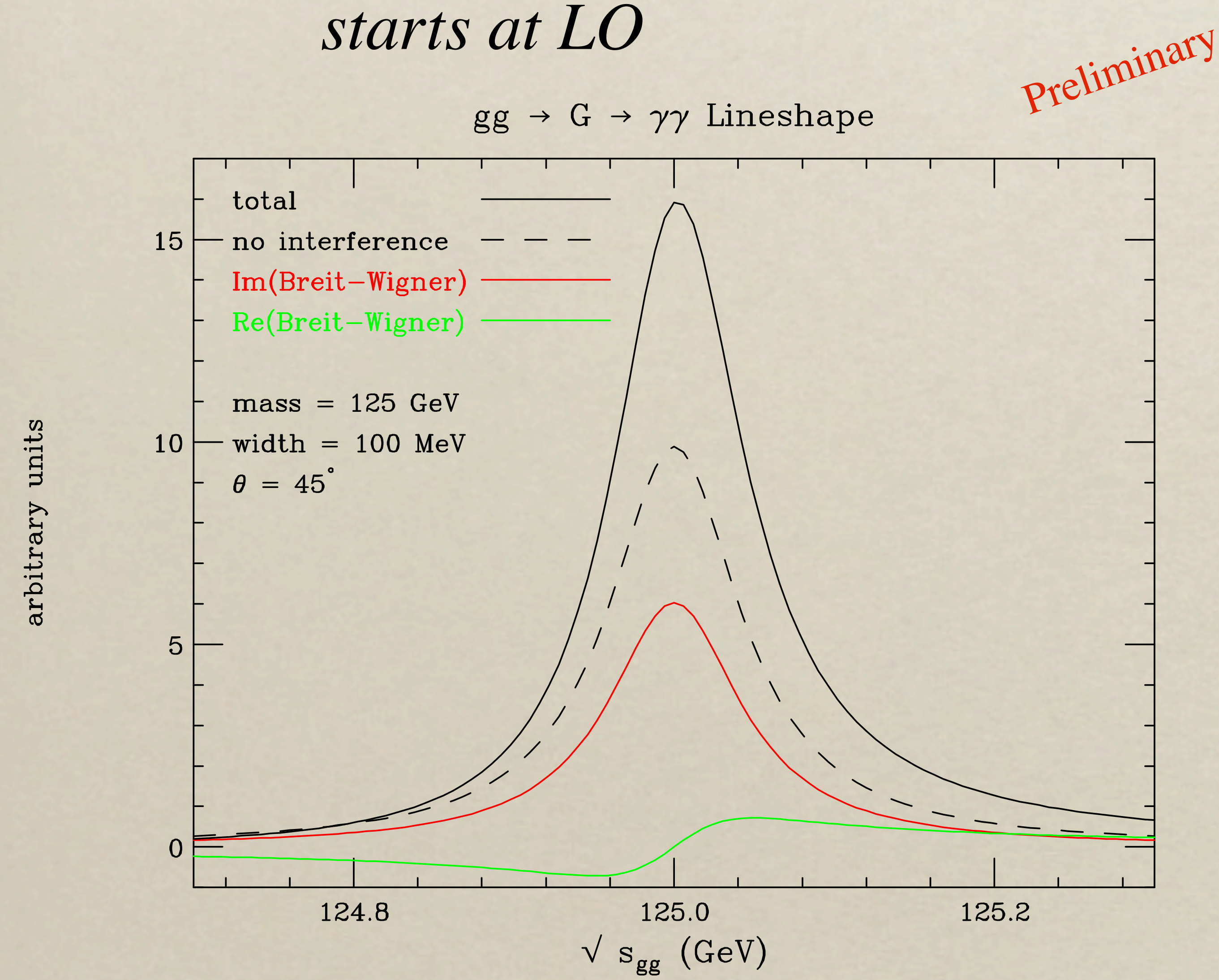
$G_{g\gamma} > 0$ for heavy graviton

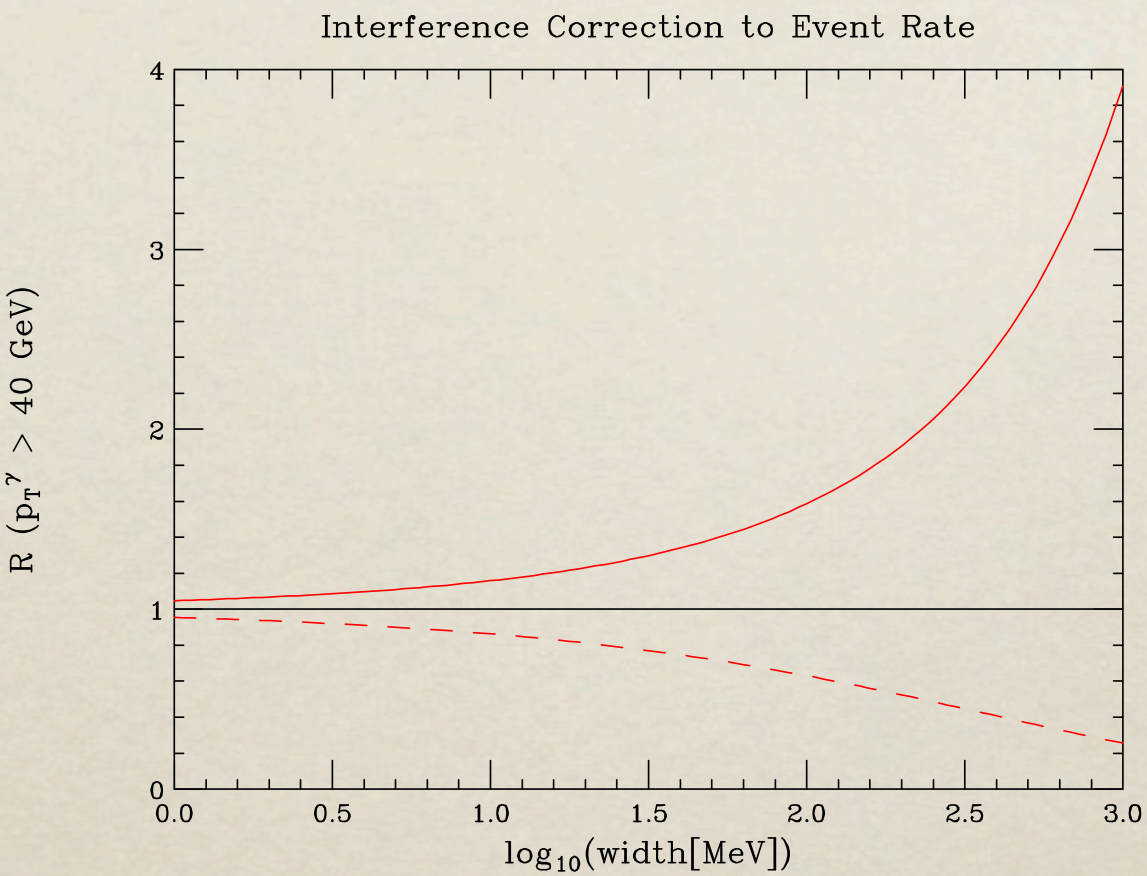


almost flat profile for small scattering angle

Interference on Signal Yields (Spin-2)

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





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