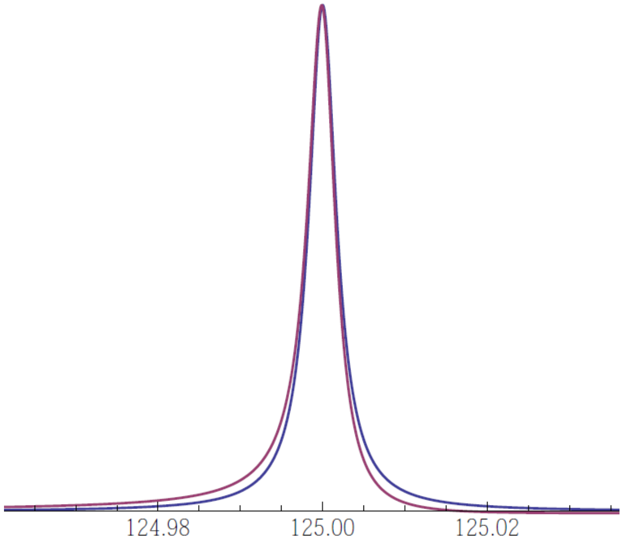
Higgs Interferometry



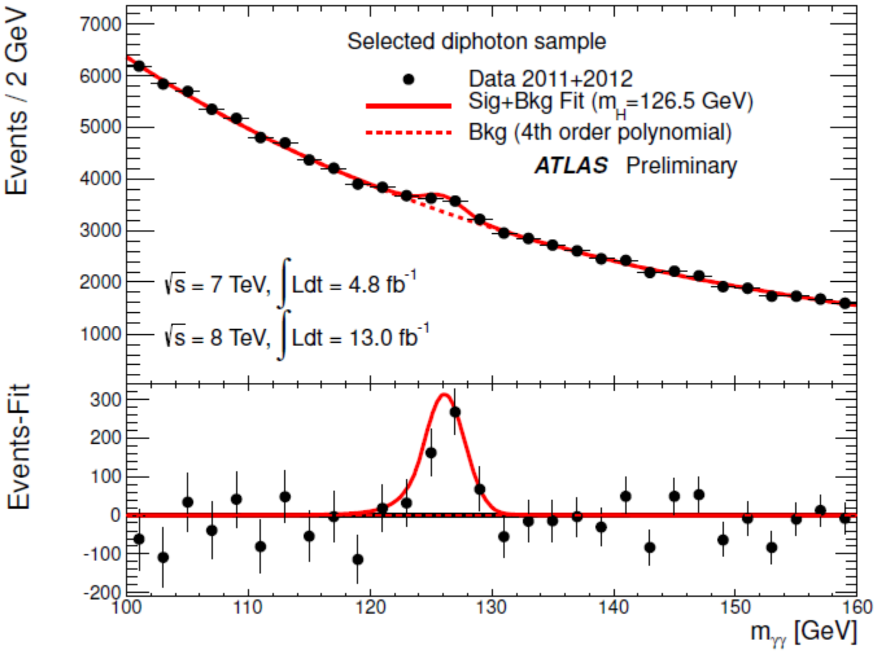
Lance Dixon (SLAC)

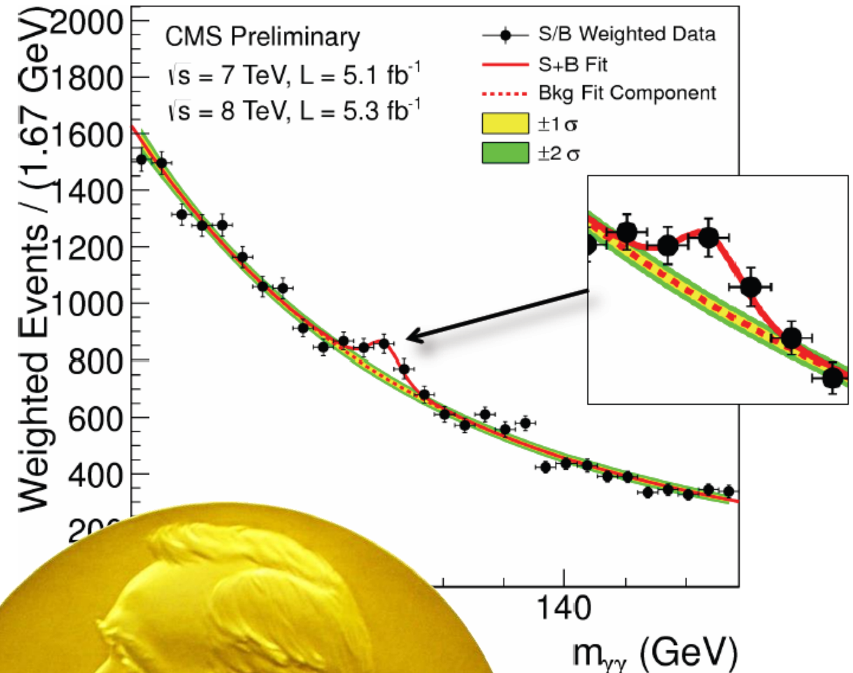
with Ye Li [1305.3854] and Stefan Höche

New Directions in Theoretical Physics

U. Edinburgh, Jan. 8, 2014

A new particle!

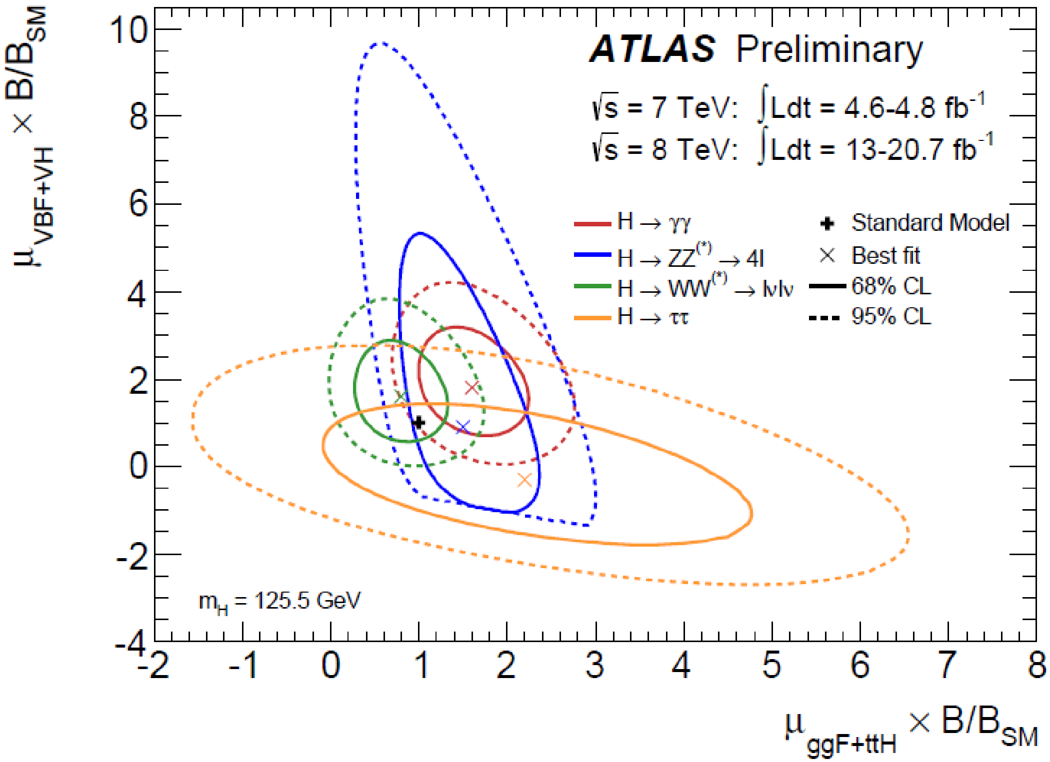




"The Higgs boson changes everything. We're obligated to understand it using all tools."

- Chip Brock at "Snowmass on the Mississippi

We know a lot about it already



- These are all measurements of σ_{prod} x Br(H→f).
- Besides adding more data and channels, what other types of measurements might add more information?

What about its lifetime?

- Most fundamental property of a particle, after its mass and spin.
- In the Standard Model,

  $\tau = 0.16 \times 10^{-21}$ s = 1/6 zs

  $c\tau = 5 \times 10^{-5}$ nm (no displaced vertices)

- Width: $1/\tau = \Gamma = 4$ MeV

Γ much smaller than typical experimental resolution on decay products, ~ 1 GeV or more.

- Direct lifetime or width measurements are not feasible at colliders (except possibly a muon collider).

Can we use event yields?

- Higgs signal strength in decay channel f:

$$\sigma_{\rm prod}(i \rightarrow {\rm H}) \cdot {\rm Br}({\rm H} \rightarrow f) = |M(i \rightarrow {\rm H})|^2 \cdot |M({\rm H} \rightarrow f)|^2 / \Gamma$$

$$= [\sigma \cdot {\rm Br}]_{\rm SM} \cdot c_i^2 \cdot c_f^2 / \Gamma$$

if we scale SM couplings of initial and final states i and f to H by factors of $c_{i,f}$

- Invariant under scaling all $c_{i,f}$ uniformly,

$$c_{i,f} \rightarrow \xi \, c_{i,f}$$

$$\Gamma \rightarrow \xi^4 \, \Gamma$$

Flat direction (unless one can observe H independently of decay mode)

Stopping the flat direction

- Often said that LHC cannot directly measure the width of the Higgs boson.
- However, using interference with the continuum background for $gg \rightarrow \gamma\gamma$, future LHC data can put [LD, Y. Li 1305.3854] a fairly direct upper limit on the Higgs width, much better than ~ 1-<u>6.9</u> GeV possible directly. CMS
- It may eventually be possible to get close to the Standard Model width of 4 MeV.
- Similar idea works for $gg \rightarrow ZZ$, far from Higgs resonance Kauer, Passarino, 1206.4803; Caola, Melnikov, 1307.4935; Campbell, Ellis, Williams, 1311.3589

“Higgs Interferometry”

How to use quantum superposition

$$|\text{Higgs}\rangle \;+\; |q\bar{q}\rangle$$

to learn something new about the Higgs (its lifetime)

Interference in $gg \to H \to \gamma\gamma$

c_g c_γ

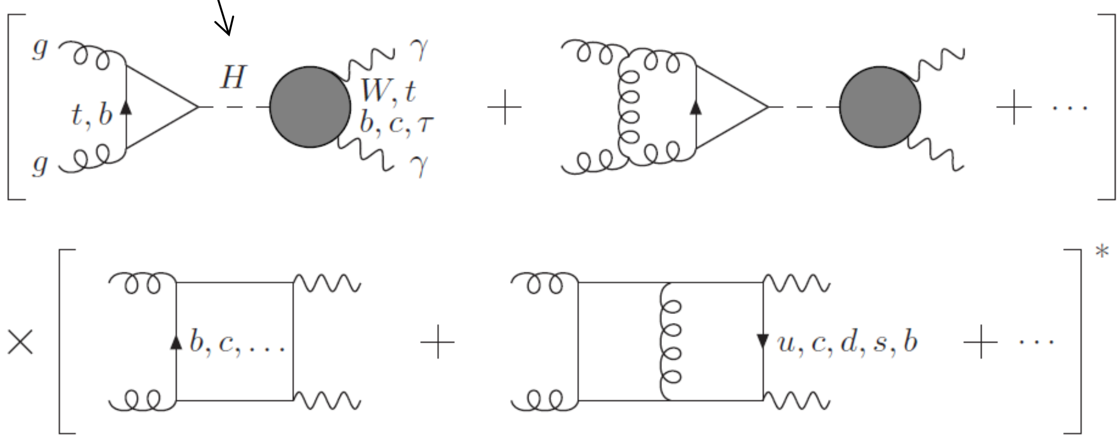
$$\mathcal{A}_{gg\to\gamma\gamma} = \frac{-\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}}{\hat{s}-m_H^2+im_H\Gamma_H} + \mathcal{A}_{\rm cont}$$

shifts peak position (apparent mass)

$$\to \quad \delta\hat{\sigma}_{gg\to H\to\gamma\gamma} = -2(\hat{s}-m_H^2)\frac{{\rm Re}\,(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\rm cont})}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2} - 2m_H\Gamma_H\frac{{\rm Im}\,(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\rm cont})}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}$$

shifts peak height (event yield)

or spin 2 "G"



(assume) dominantly real

Interference effects and Γ

LD, Y. Li 1305.3854

- All non-interference measurements at LHC give signal strength proportional to $c_i^2 \cdot c_f^2 / \Gamma$
- Invariant under scaling all $c_{i,f}$ uniformly,

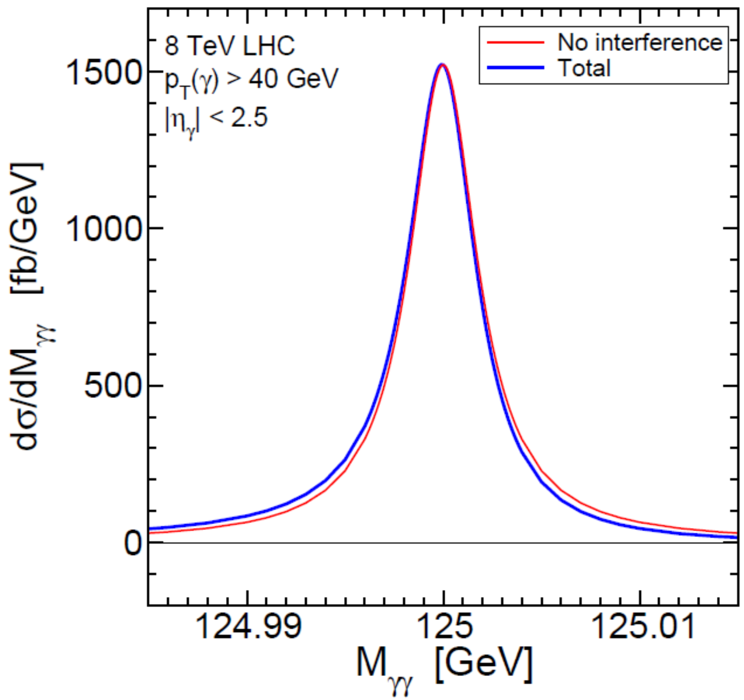
$$c_{i,f} \rightarrow \xi\, c_{i,f}$$
$$\Gamma \rightarrow \xi^4\, \Gamma$$

- Allow for non-SM, undetectable modes in Γ
- Interference effects go like $c_i \cdot c_f$, break this degeneracy
- Allow one to measure or bound Higgs width

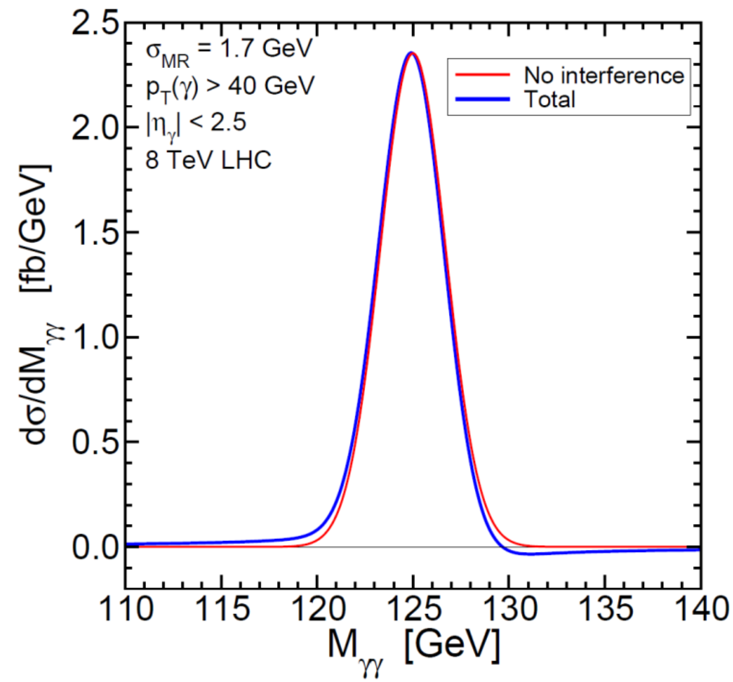
Mass shift from real part

S. Martin, 1208.1533, 1303.3342; D. de Florian et al, 1303.1397

Smear lineshape with Gaussian with width σ = 1.7 GeV



→

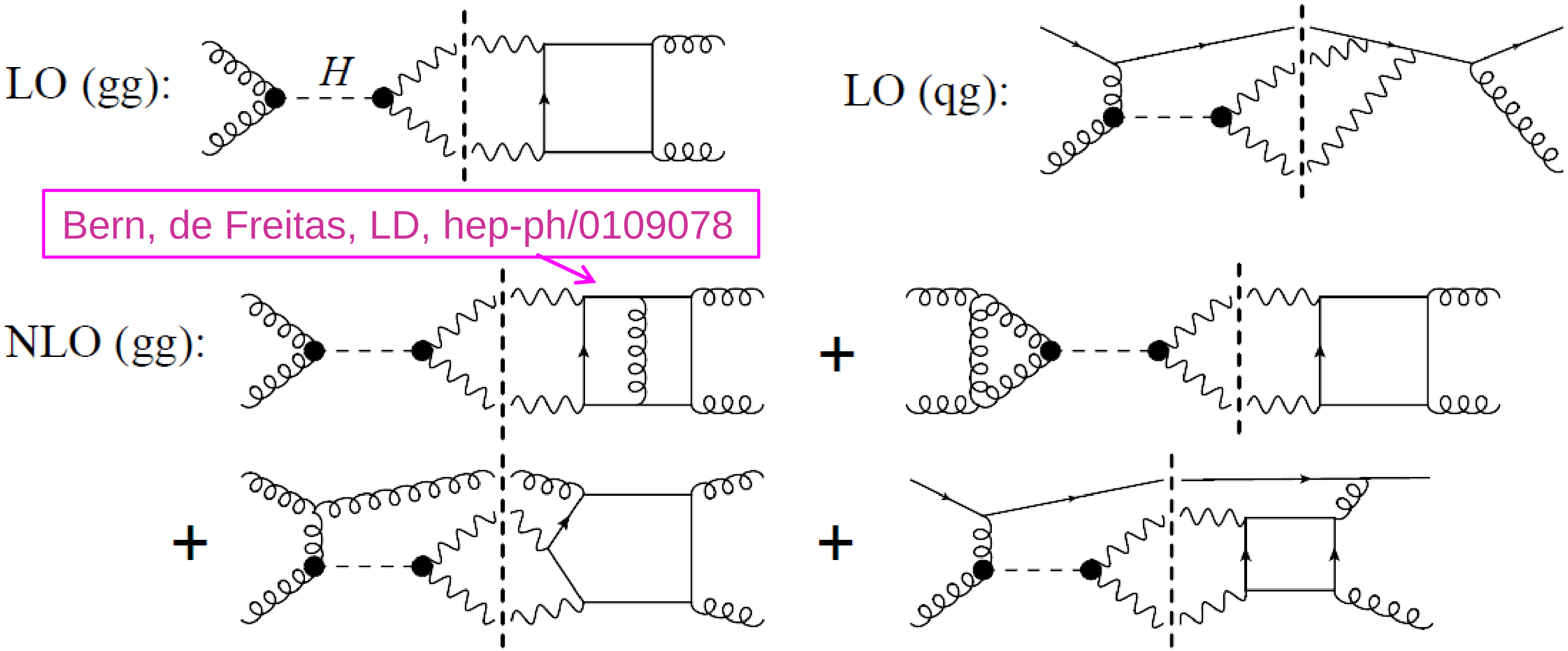


Perform least squares fit to Gaussian at mass $M + \delta M$

→ δM ~ 100 MeV in SM at LO

Diagrams for NLO mass shift

LD, Y. Li, 1305.3854

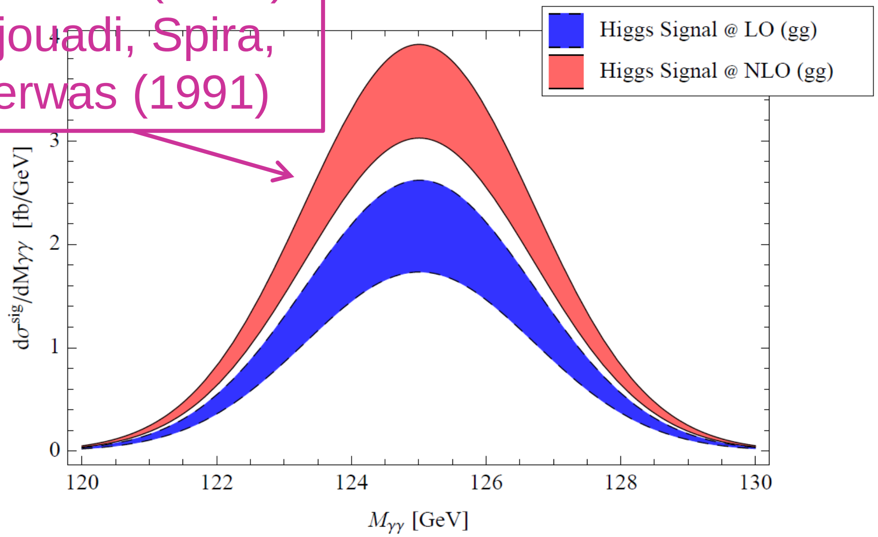


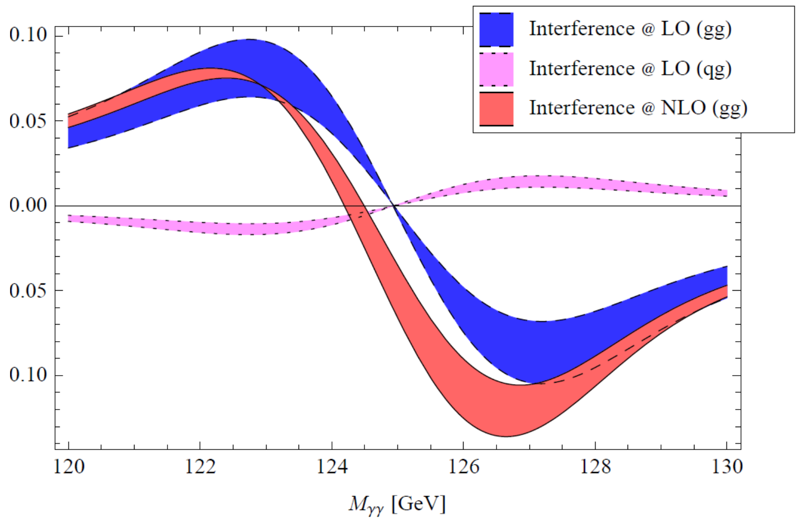
Mass shift at NLO

- Reduced by 40% from LO

LD, Y. Li, 1305.3854

Dawson (1991); Djouadi, Spira, Zerwas (1991)

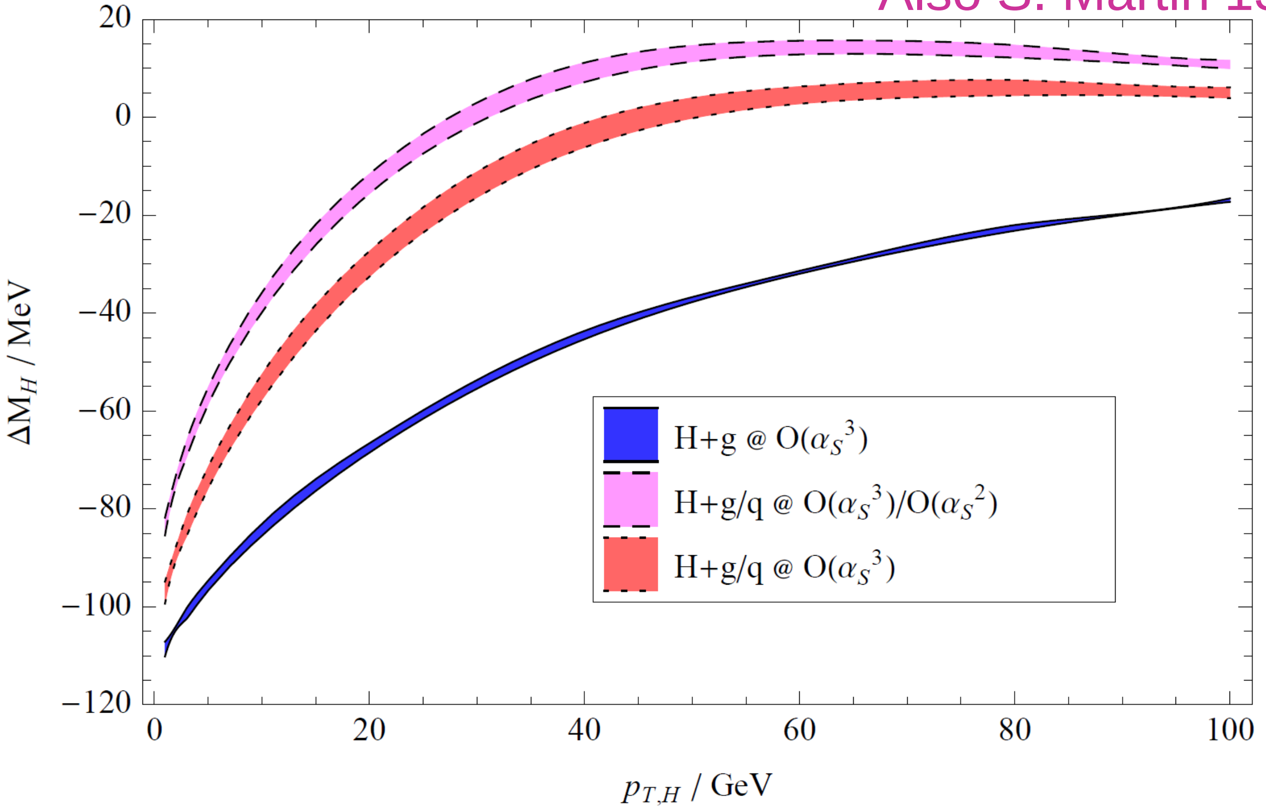




- Interference increases, but signal increases more

NLO mass shift vs. lower cut on Higgs p_T

Also S. Martin 1303.3342



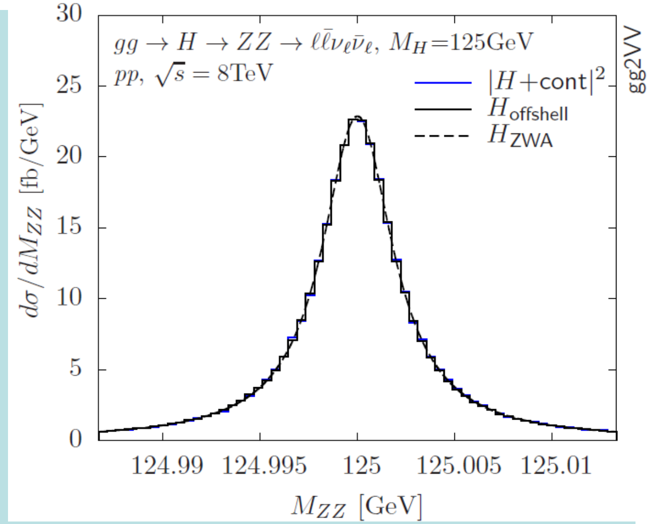
- Big cancellation between gg and qg channel at large p_T
- Allows use of p_T > 30 or 40 GeV sample as "control" mass

"Control Mass" Critical

- We have no a priori knowledge of the Higgs boson mass at the 1 GeV level
- The Higgs boson mass must be measured in two high statistics, high precision samples that are affected differently by interference effects
- Only realistic channels are $\gamma\gamma$ and $ZZ^* \rightarrow l^+ l^- l^+ l^-$
- Low p_T versus high p_T $\gamma\gamma$ is one possibility

Two other possible control masses

Kauer, Passarino, 1206.4803



1. ZZ* → 4 leptons

Great theoretically $(\delta M_{ZZ} << \delta M_{\gamma\gamma})$ →

But experiments differ

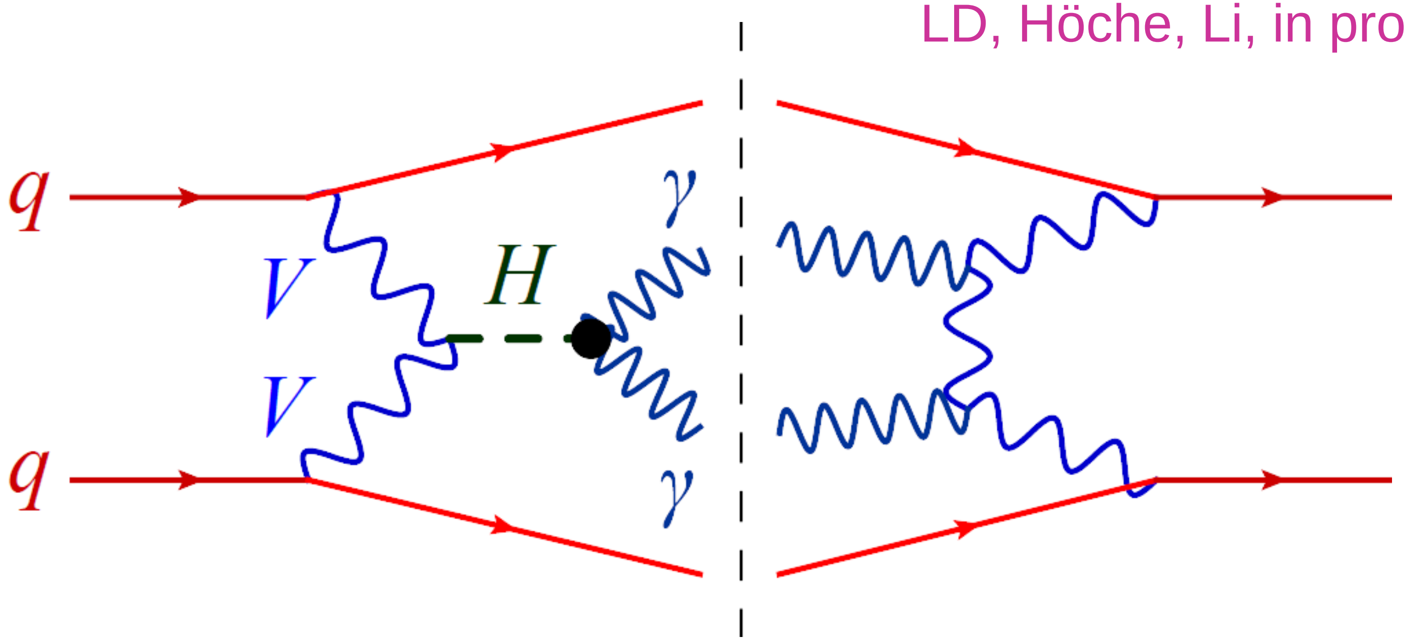
$$m_H^{\gamma\gamma} - m_H^{ZZ} = +2.3^{+0.6}_{-0.7} \pm 0.6 \text{ GeV (ATLAS)}$$
$$= -0.4 \pm 0.7 \pm 0.6 \text{ GeV (CMS)},$$

2. Mass in $\gamma\gamma$ in VBF enhanced sample

In general, comparing two $\gamma\gamma$ masses might reduce systematic uncertainties associated with e → γ energy calibration

Mass shift in VBF

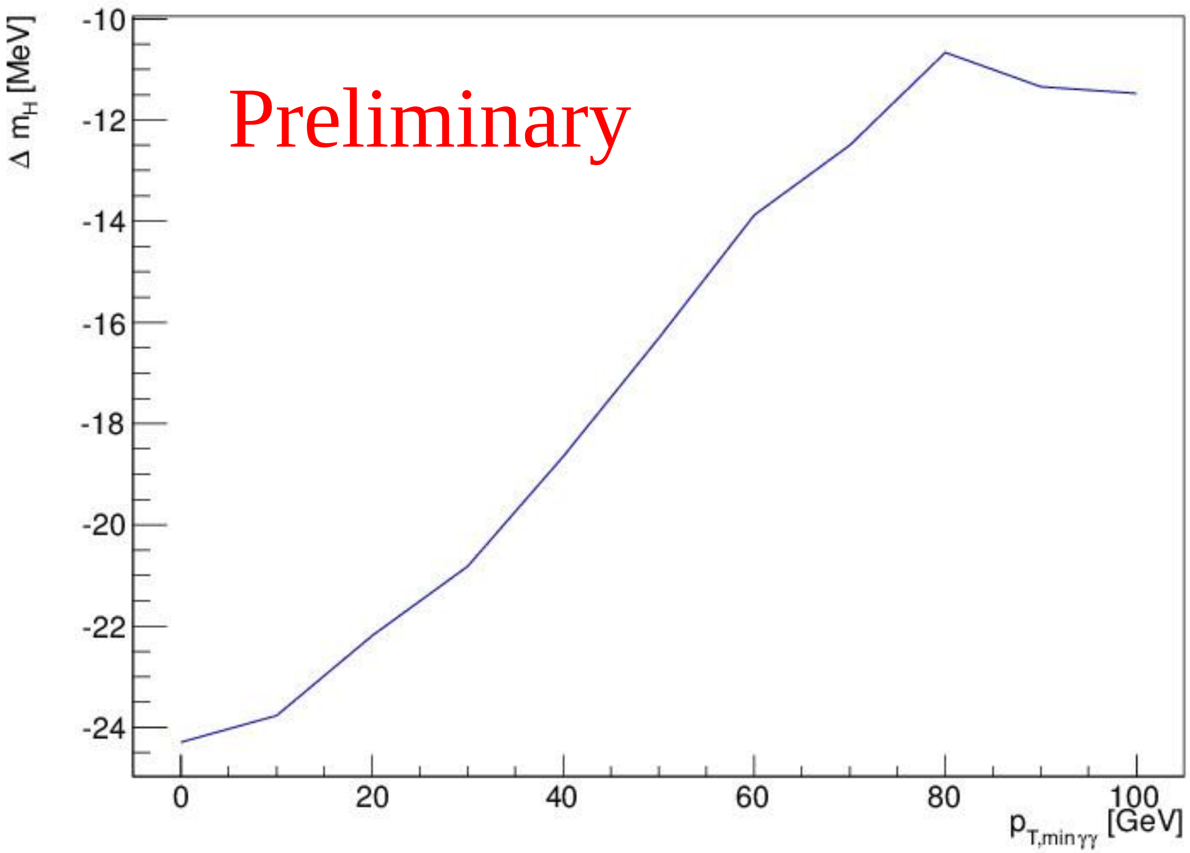
LD, Höche, Li, in progress



V = W or Z.

W channel should dominate mass shift because background photons can be more central when radiated off of charged *W* line in *t* channel

Mass shift in VBF (cont.)



$p_T(\gamma_{1,2})$ > 20 GeV
$|\eta(\gamma_{1,2})|$ < 2.5

$p_T(j_{1,2})$ > 20 GeV
M_{jj} > 800 GeV
$|\Delta\eta(jj)|$ > 4

- About 1/3 of effect in gluon fusion, and same sign
- Also declines as cut on minimum Higgs p_T is raised

Mass shift increases with Γ

- Non-interference measurements at LHC give signal proportional to $c_i^2 \cdot c_f^2 / \Gamma$
- Hold this fixed.
- Interference effects go like $c_i \cdot c_f \sim \sqrt{\Gamma}$

Coupling vs. width

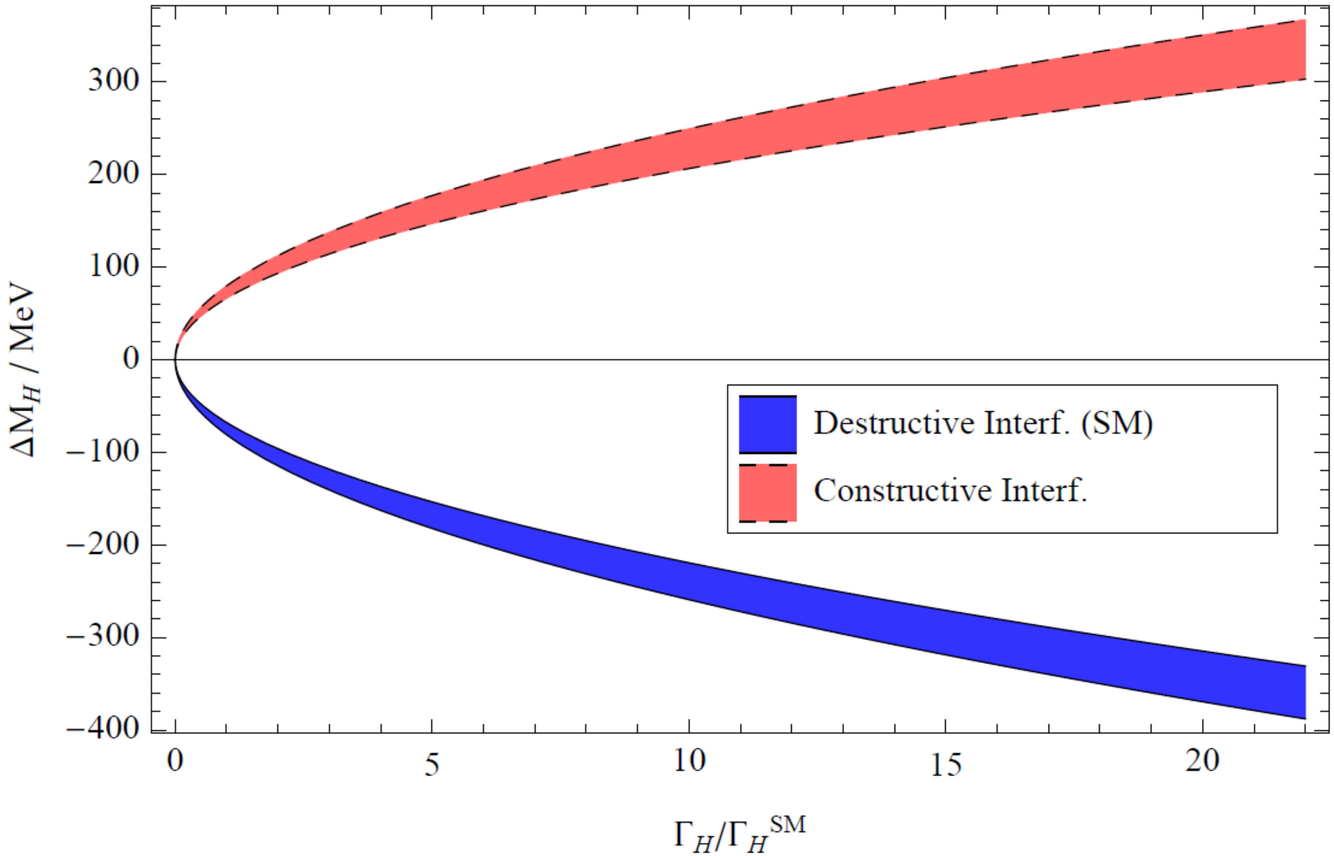
$$\mathcal{L} = -\left[\frac{\alpha_s}{8\pi} c_g b_g G_{a,\mu\nu} G_a^{\mu\nu} + \frac{\alpha}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \frac{h}{v}$$

- Coupling product $c_g \cdot c_\gamma = c_{g\gamma}$ determined by requiring that event yield is unaffected:

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

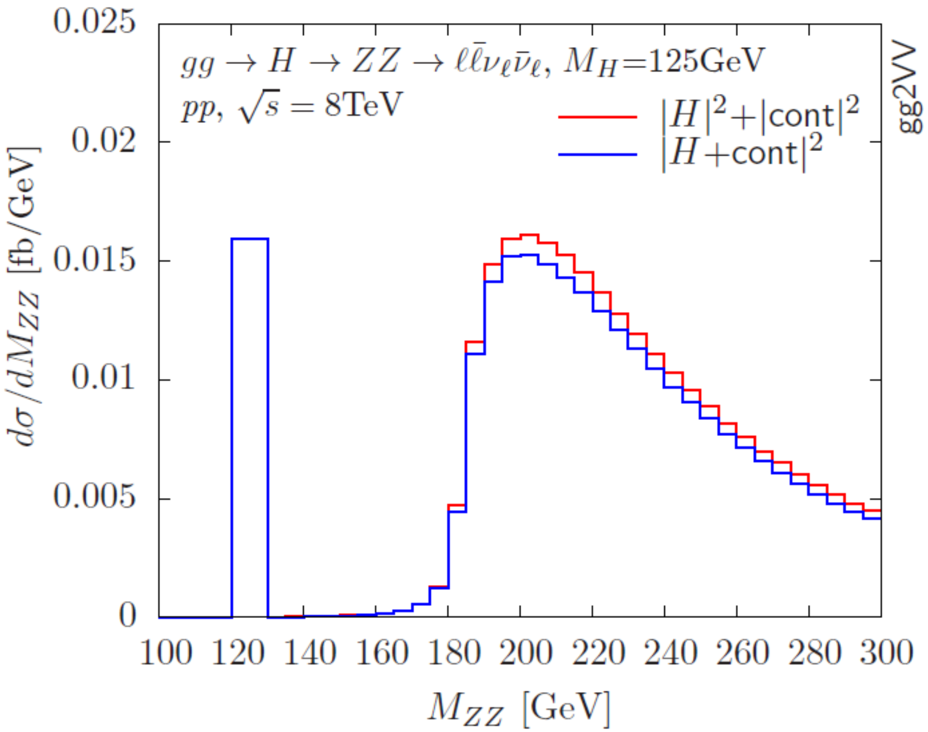
- Ignoring I, $c_{g\gamma} = \sqrt{\mu_{\gamma\gamma} \Gamma_H / \Gamma_H^{SM}}$

Mass shift vs. width in $gg \to \gamma\gamma$



- Measurement of ΔM statistically limited now, ~ 800 MeV
- Systematically limited in HL-LHC era, ~ 100-200 MeV

Interference in $gg \rightarrow H \rightarrow ZZ$



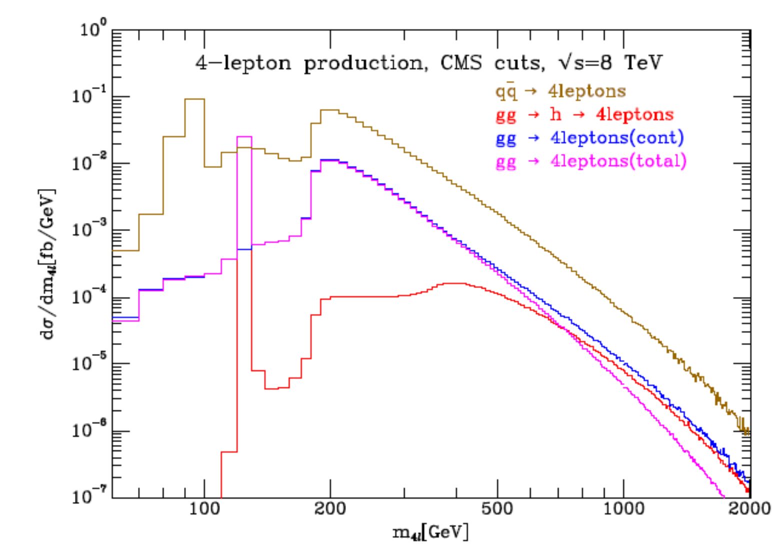
Kauer, Passarino, 1206.4803

ZZ production at high mass dominated by $q\bar{q}$, not *gg*

Still, if interference effect is increased enough, by $c_g \cdot c_Z \sim \sqrt{\Gamma}$, would get too much depletion of observed ZZ signal Caola, Melnikov, 1307.4935; Campbell, Ellis, Williams, 1311.3589

Bound on Γ from high mass ZZ

- Caola, Melnikov suggest $\Gamma_H < 20\text{–}40\ \Gamma_{SM}$ already with present LHC data.
- Campbell, Ellis, Williams ~ confirm, use kinematic discriminants to "improve" limits:



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

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

→

$$\Gamma_H < 43.2\,\Gamma_H^{SM} \text{ at 95\% c.l.,} \quad (m_{4\ell} > 130 \text{ GeV analysis})$$
$$\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at 95\% c.l.,} \quad (m_{4\ell} > 300 \text{ GeV analysis})$$

Still only LO analysis of interference, and gg component of background. Will be systematically limited at some point.

Similar recent results in WW channel: CEW, 1312.1628

From real part to imaginary part

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

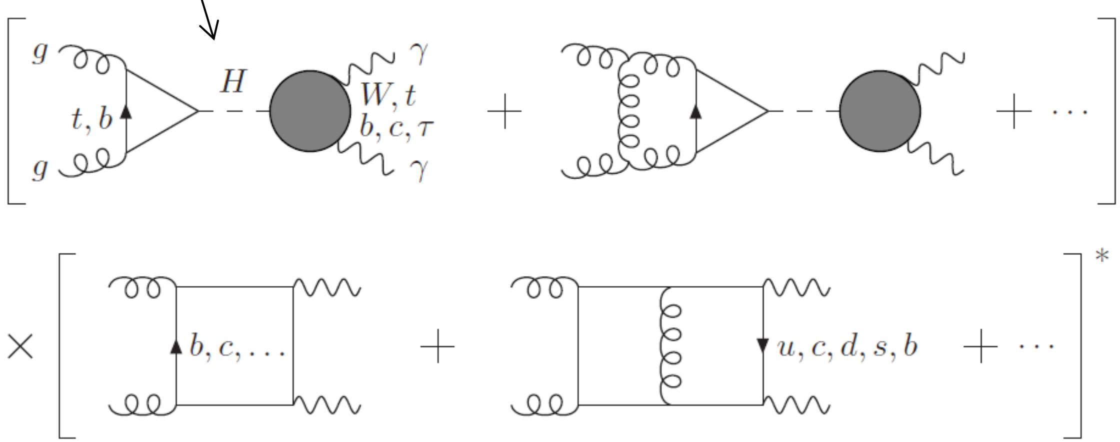
shifts peak position (apparent mass)

$$\rightarrow \quad \delta\hat{\sigma}_{gg\to H\to\gamma\gamma} = -2(\hat{s} - m_H^2)\frac{\text{Re}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\text{cont}}\right)}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma_H^2}$$

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

shifts peak height (event yield)

or spin 2 “G”



(assume) dominantly real

What if it's spin 2?

What about spin 2?

LD, Höche, Li, to appear

- Rejection of spin 2 hypothesis vs. spin 0 uses distribution in $\cos\theta^*$ for $gg \to \gamma\gamma$.

[Recent ZZ analysis CMS 1312.5353 prefers spin 0.]

- Without interference, distribution is unambiguous:

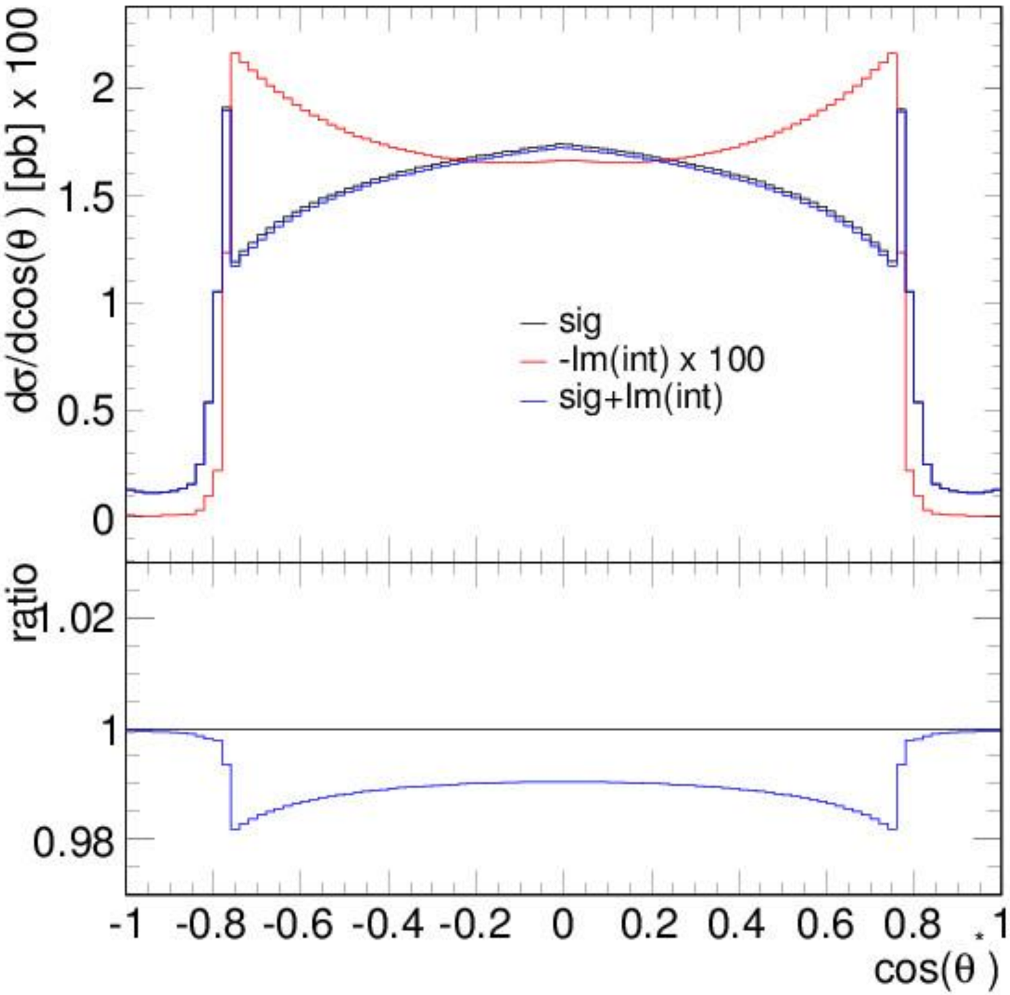
~ 1 spin 0

~ $1 + 6\cos^2\theta^* + \cos^4\theta^*$ 2_m^+

- How much distortion from interference effects [Im part]?
- SM Higgs: < few % LD, Siu, hep-ph/0302233

Spin 0 (SM) $\cos\theta^*$ distortion

Including typical acceptance cuts



LD, Siu, hep-ph/0302233 ;
LD, Höche, Li, to appear

Spin 2 distortion could be much bigger, because:

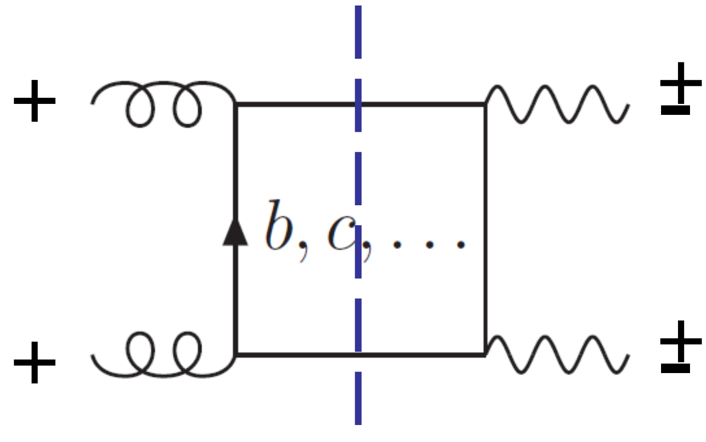
- Im part anomalously small in spin 0 channel.
- Spin 2 width unknown

in Collins-Soper frame

Strong helicity dependence of Im part of background 1-loop amplitude

Spin 0

Im

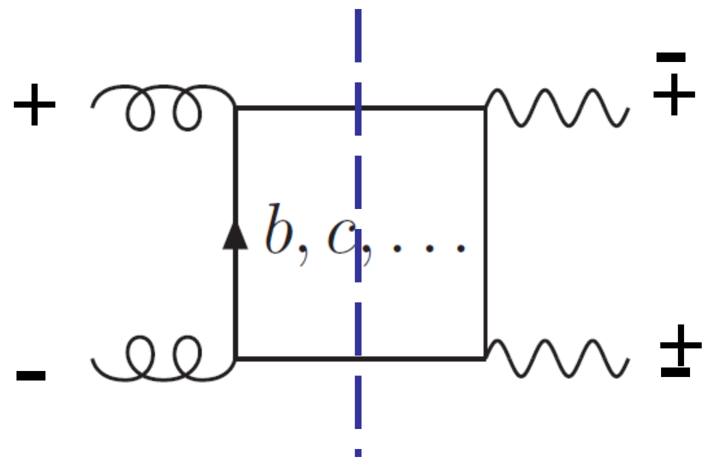


$= O(m_q^2/m_H^2) \sim 0$

Dicus, Willenbrock (1988)

Spin 2_m^+

Im

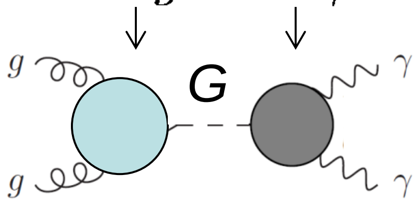


$= O(1)$

Non-minimal spin 2 can interfere with other helicity amplitudes, but only this helicity config. has Im part

(spin 2) - 1-loop interference simple

$$G_g \times G_\gamma \;\equiv\; G_{g\gamma}$$



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

where $c = \cos\theta$

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

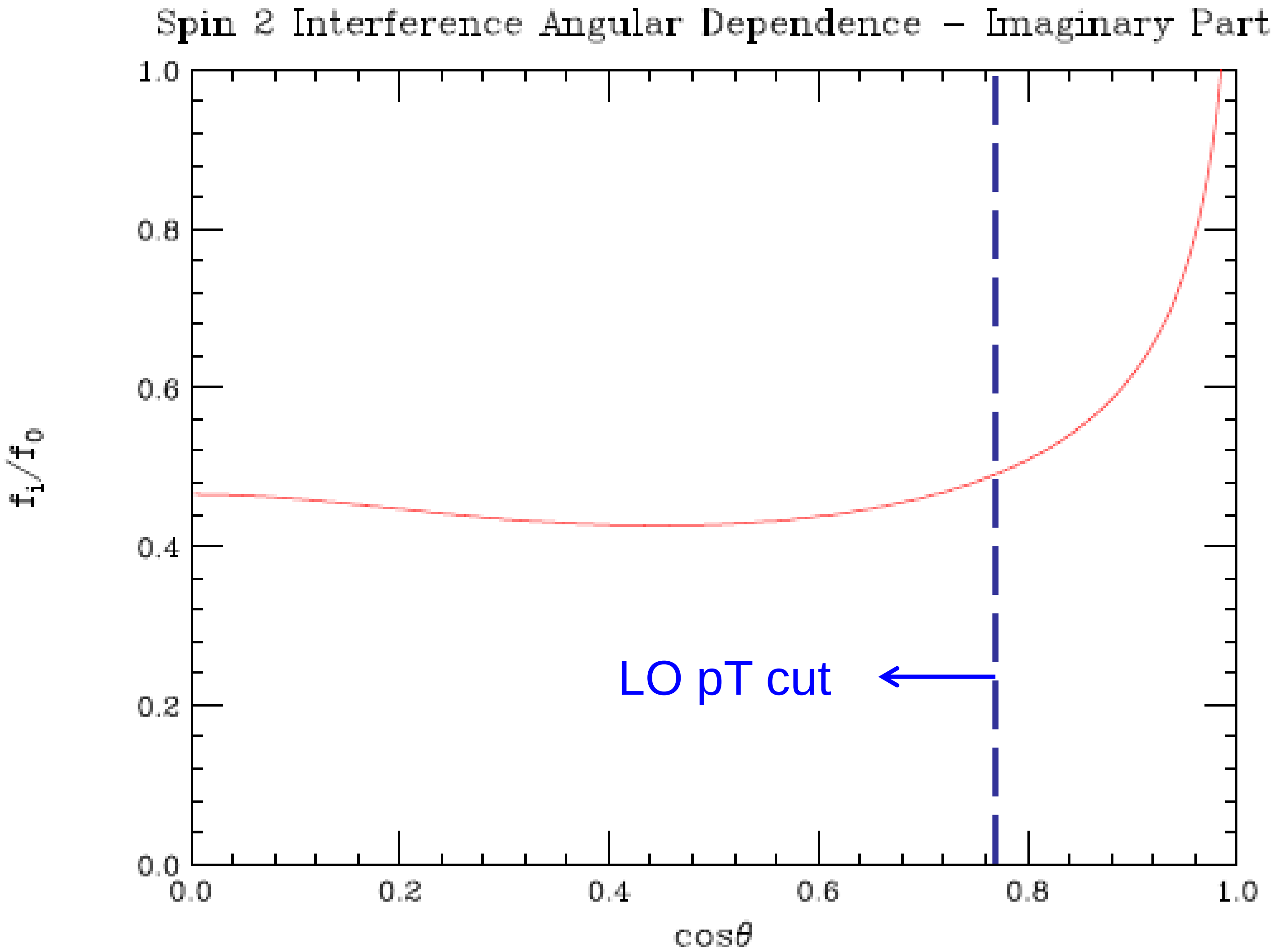
$$f_i(c) = 2\left[\left(1+\frac{(1-c)^2}{4}\right)\ln\left(\frac{2}{1-c}\right) + \left(1+\frac{(1+c)^2}{4}\right)\ln\left(\frac{2}{1+c}\right)\right] - 3 + c^2,$$

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

and

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

Im part remarkably flat in cosθ

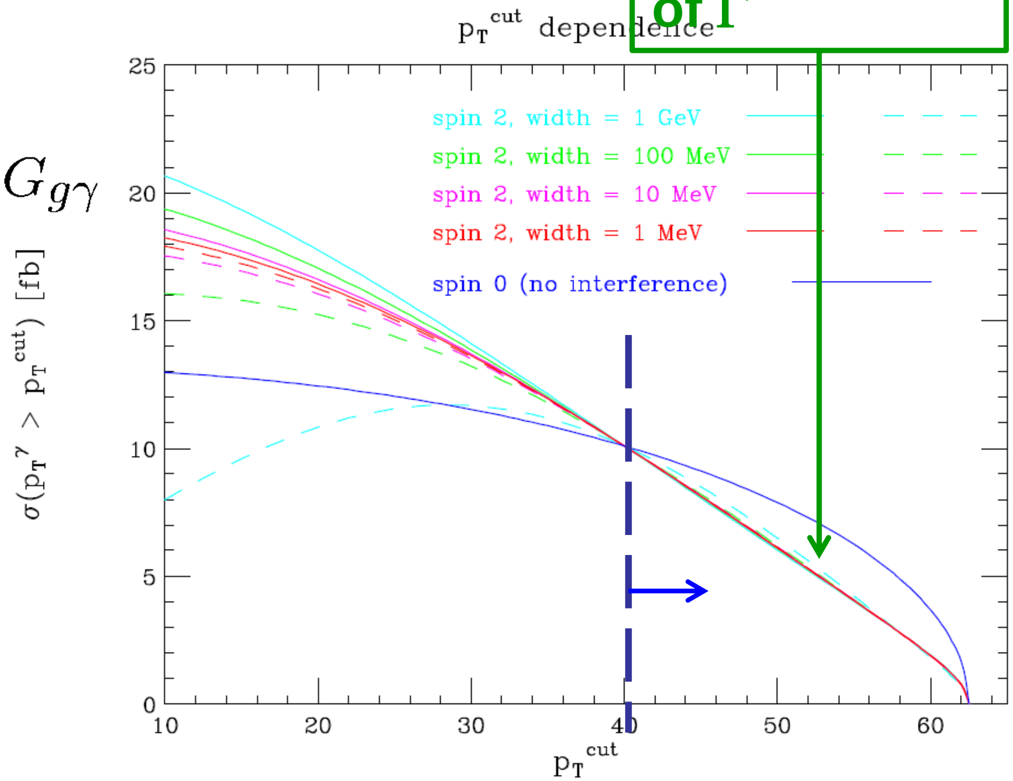


Size of interference as function of width Γ

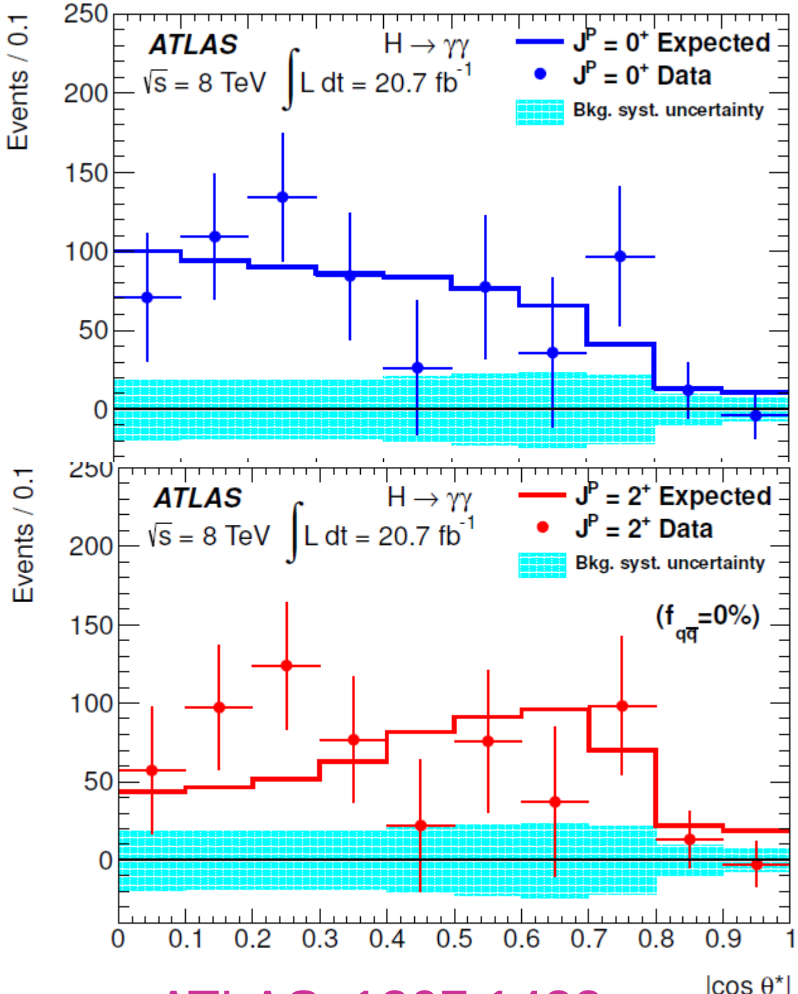
- Event yield ~ $c_1 G_{g\gamma}^2 + c_2 G_{g\gamma}\Gamma$
- Normalize to SM Higgs at photon p_T^{cut} = 40 GeV.
- Quadratic equation for $G_{g\gamma}$
- Constructive, destructive solutions

- Completely model independent with respect to coupling strengths, other channels.

Almost independent of Γ

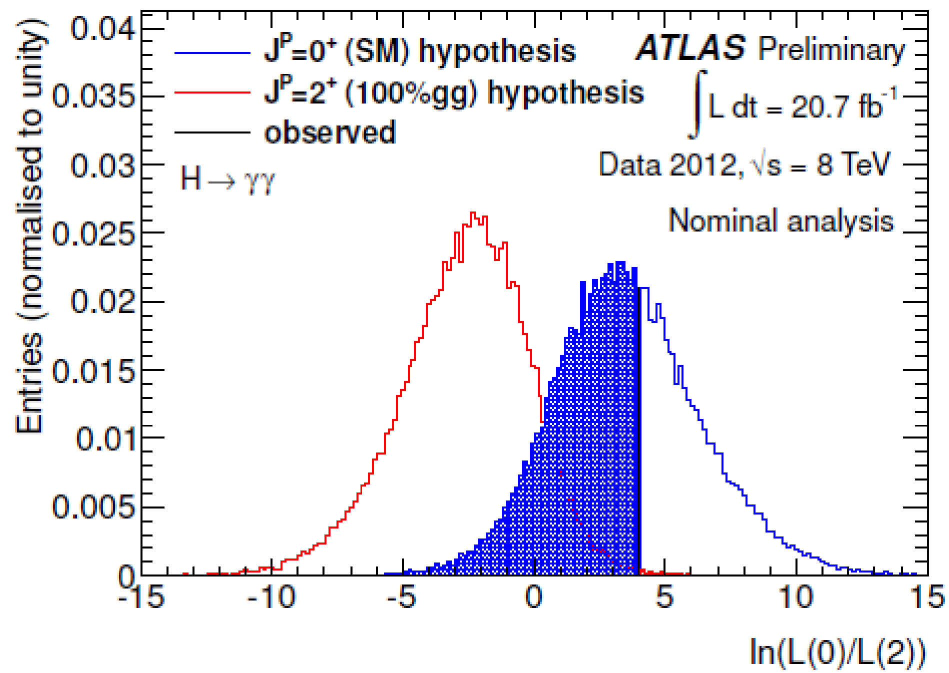


ATLAS likes spin 0



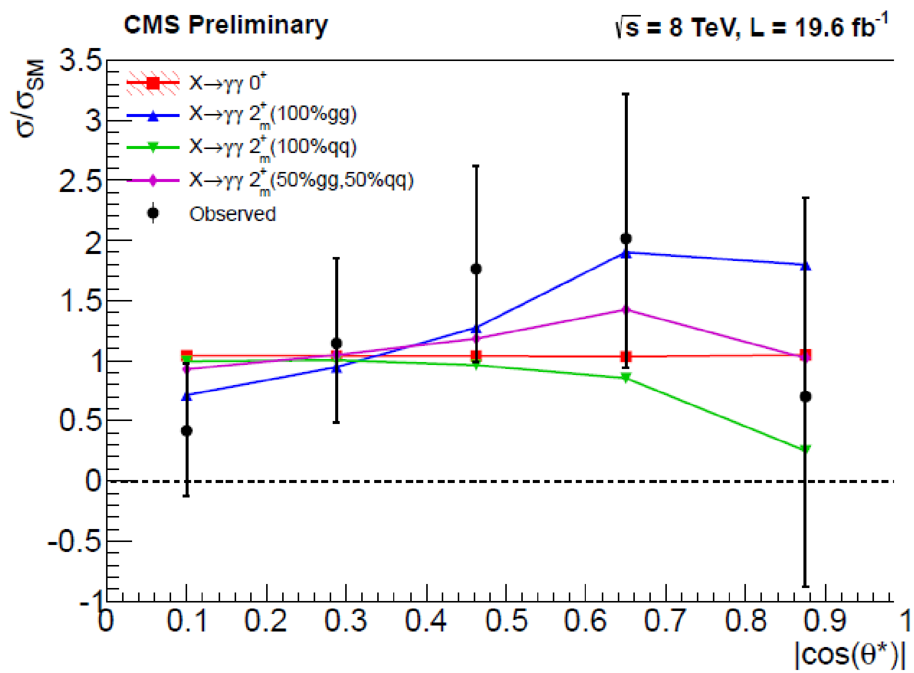
ATLAS, 1307.1432

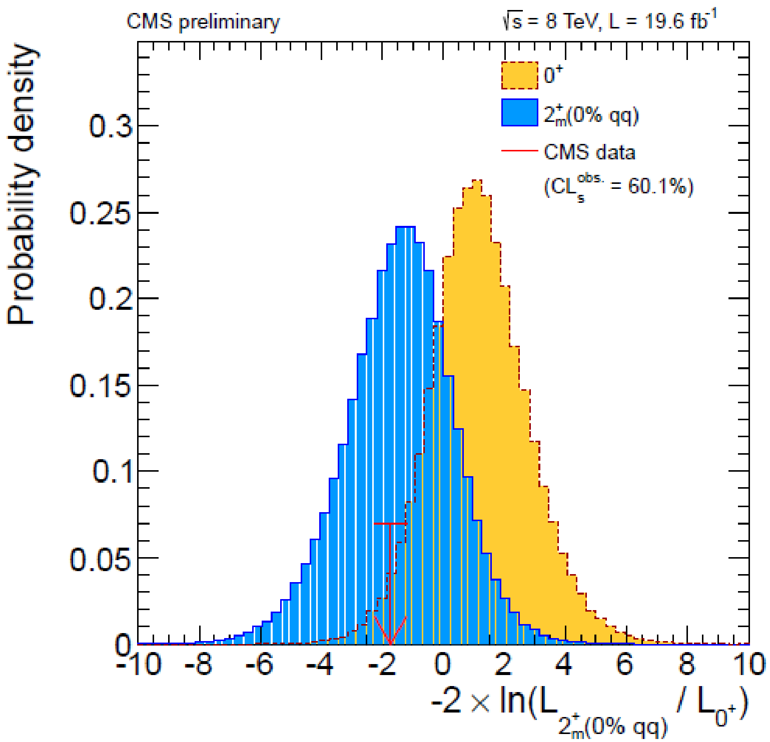
99% exclusion of *gg* → *spin 2* → *γγ*



ATLAS-CONF-2013-029

CMS actually likes spin 2 (in $\gamma\gamma$)



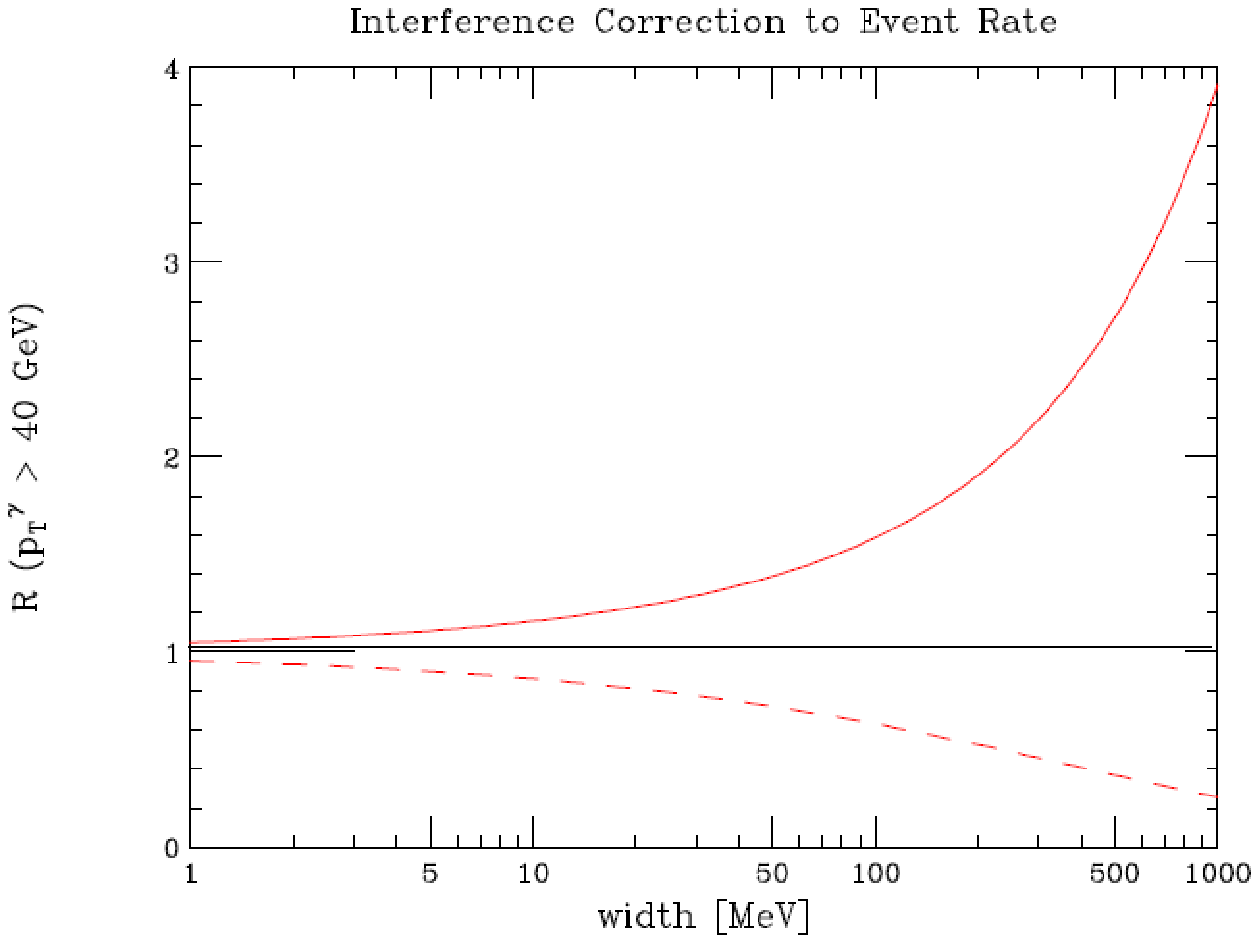


CMS-PAS-HiG-13-016

Compatibility

Source	χ^2 p-value
Data vs. 0^+	0.68
Data vs. 2^+_m (100% gg)	0.91
Data vs. 2^+_m (100% $q\bar{q}$)	0.51
Data vs. 2^+_m (50% gg, 50% qq)	0.81

Spin 2 yield might be strongly affected – even if cosθ* distribution is not

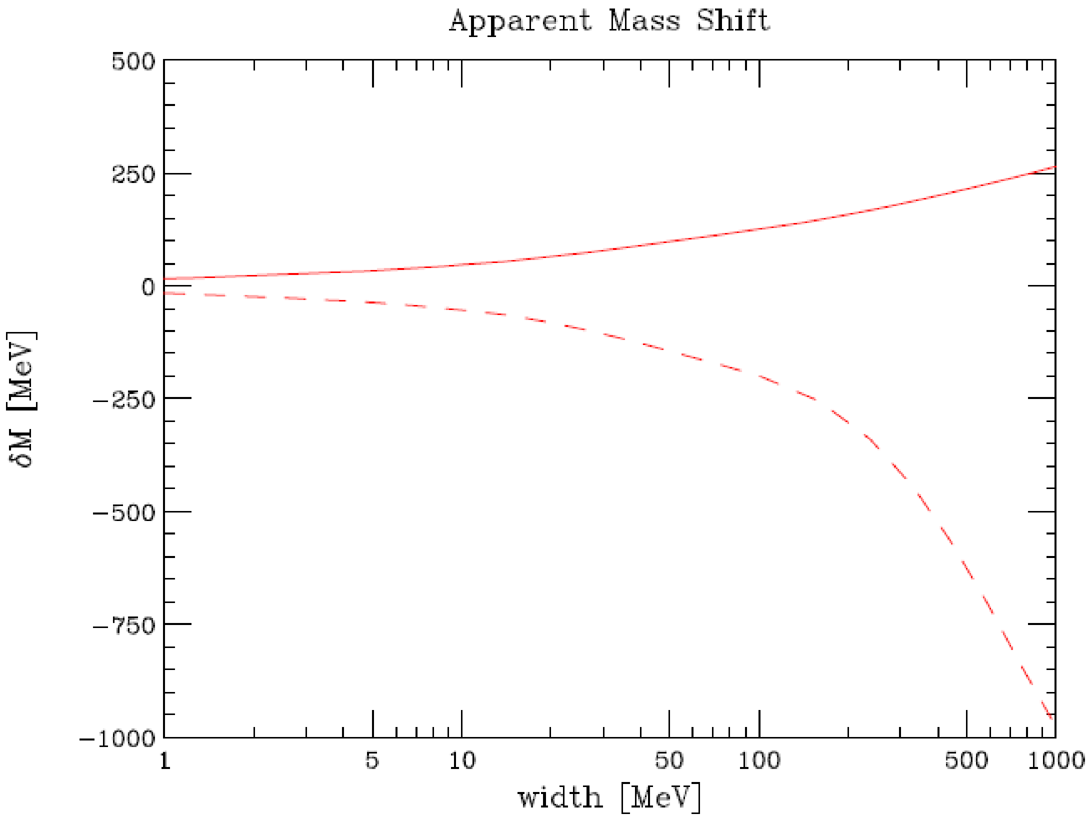


Conclusions

- Interference effects, in particular the mass shift in $\gamma\gamma$, should allow bounding the Higgs width to well under the direct experimental resolution, maybe eventually approaching the SM width.
  Now under study experimentally.
- At least 3 possible control masses.
- In principle, interference effects also important for testing non-SM hypotheses – e.g. spin 2 in $\gamma\gamma$.
  In practice, distortion of the $\cos\theta^*$ distribution is very small – where it is measurable.

Spin-2 mass shift from real part

Smear lineshape with Gaussian with width σ = 1.7 GeV.
Do least squares fit to Gaussian at mass $M + \delta M$.



NLO mass shift vs. jet veto p_T