Interference effects in $gg \to H \to Z\gamma$ beyond leading order

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Higgs Hunting
IJCLab Orsay & APC Paris
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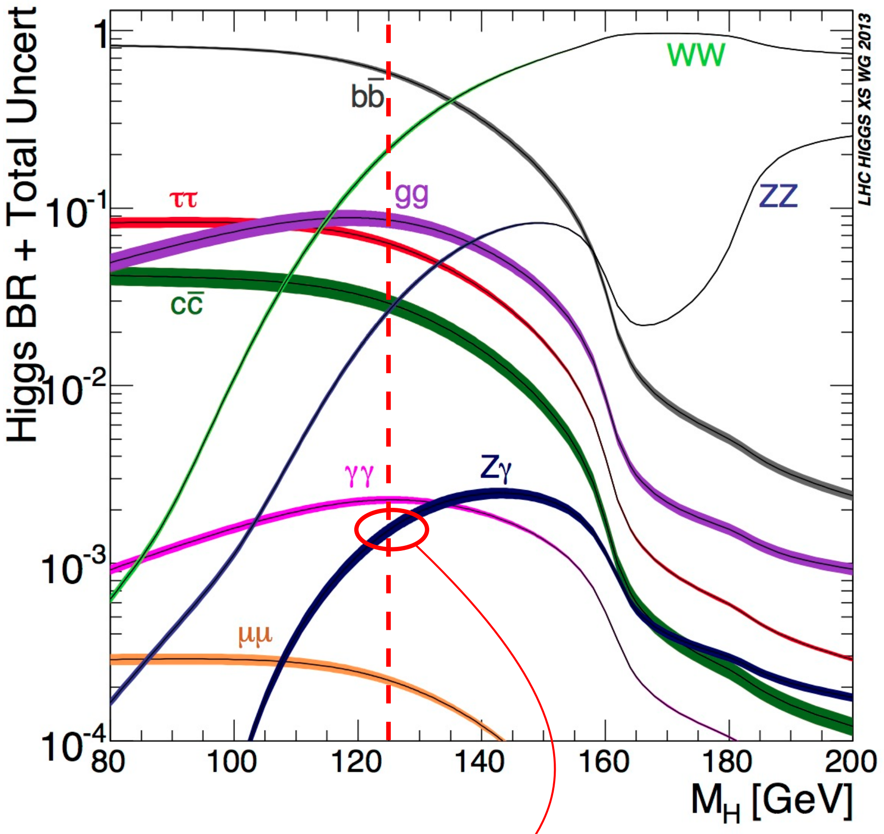
based on Phys.Lett.B 851 (2024) 138596 [arXiv:2312.12384]

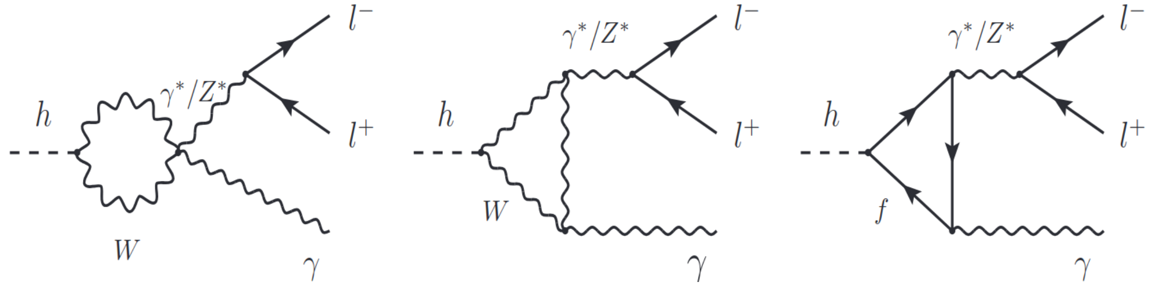
in collaboration with: F. Devoto, A. Djouadi, J. Ellis, J. Quevillon and L. Tancredi

The elusive H→ Zγ decay



$\mathrm{BR}(H\to Z\gamma) \sim 1.54 \times 10^{-3}$

- Loop-induced decay (quantum-level structure)
  sensitive to effects in several BSM scenarios
  complementary info wrt $H\to\gamma\gamma$ and $H\to gg$
- (in the SM) Only Higgs decay to two different particles
  neither two identical bosons nor particle anti-particle pair
- Really the full "Dalitz decay" : $H\to Z(\to f\bar{f})\gamma$. Take $Z\to l^+l^-$ as cleanest Z decay mode



$\mathrm{BR}(H\to Z\gamma) \times \mathrm{BR}(Z\to l^+l^-) \sim 5 \times 10^{-5} \sim 2.27\ \%\ \mathrm{BR}(H\to\gamma\gamma)$

A fully inclusive calculation $\mathrm{BR}(H\to e^+e^-\gamma)/\mathrm{BR}(H\to\gamma\gamma) \sim 5.7\%$ [Sun, Chang, Gao 1303.2230]

1. cut on leptons invariant mass: $\Gamma(H\to Z\gamma)$ pseudo-observable [Passarino 1308.0422]
2. extremely rare decay: very hard to measure

Evidence for H → Zγ decay

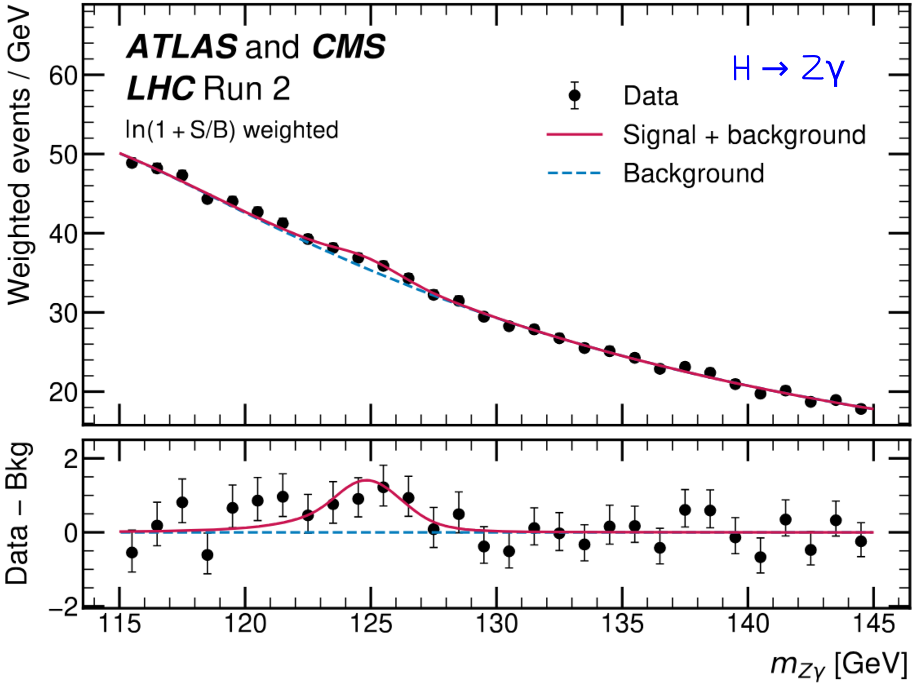
H → Zγ

May 2023

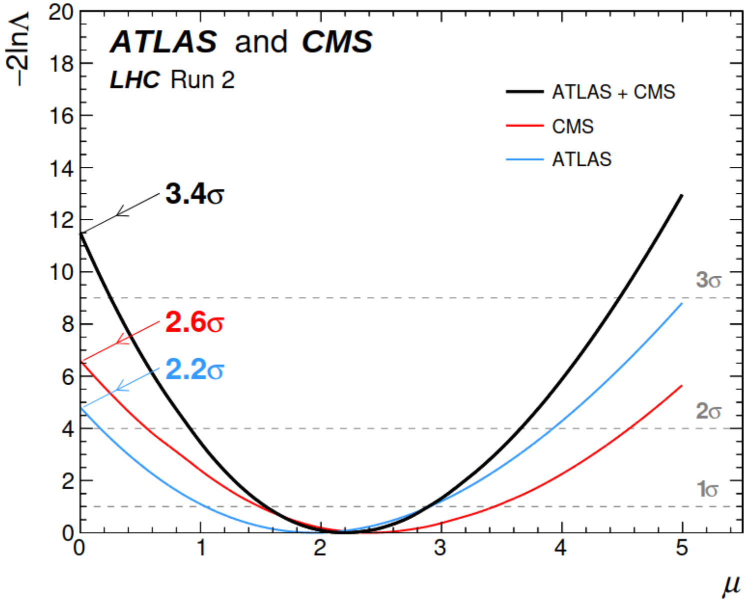
Evidence for the Higgs boson decay to a *Z* boson and a photon at the LHC

The ATLAS and CMS Collaborations

[ATLAS + CMS, Phys. Rev. Lett. 132, 021803]



Z decaying to muon and electron pairs. Evidence @ 3.4σ



Meaured BR(H → Zγ)

$(3.4 \pm 1.1) \times 10^{-3}$

agreement with SM ~ 1.9σ

"The uncertainties in the results are dominated by the statistical fluctuations of data"

[ATLAS+CMS, Phys. Rev. Lett. 132, 021803]

Observed (expected) signal strength μ:

μ = 2.2 ± 0.7 (1.0 ± 0.6 (stat.) ± 0.2 (syst.))

currently:
Tension SM prediction vs signal yield

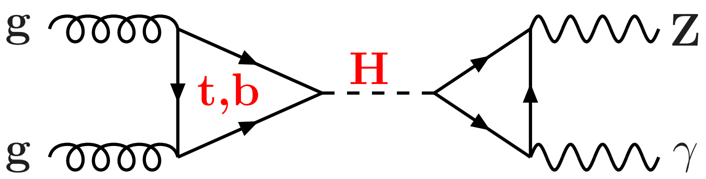
H → γγ*

Evidence for Higgs boson decays to a low-mass dilepton system and a photon in *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

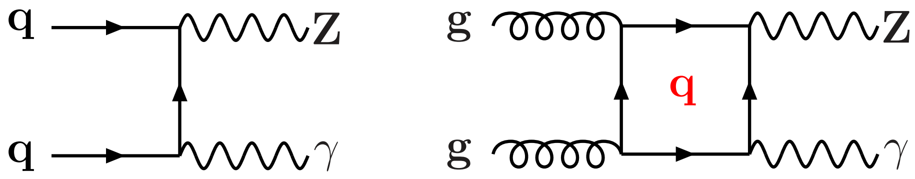
[Phys. Lett. B 819, 2103.10322]

pp→Zγ in the SM: signal & background

gg → H → Zγ (signal)



gg → Zγ (background)



see S. Jones's talk

state of the art

Higgs production in ggF (reporting only QCD here)

N^{3}LO in the HTL [Anastasiou et al 1503.06056, Mistlberger 1802.00833]

NNLO in full SM (top + bottom) [Czakon et al 2105.04436, 2312.09896]

Higgs decay to Zγ

NLO QCD [Spira et al Phys.Lett.B 276 (1992) 350-353, Gehrmann et al 1505.00561]

$\sim$ 0.3% of LO

NLO EW [Chen et al 2404.11441, Sang et al 2405.03464]

$\sim$ 7% of LO

Zγ production in pp collisions

NNLO QCD accuracy (qqb channel) [Grazzini et al 1504.01330]

gg fusion starts NNLO: contribution small [Grazzini et al 1504.01330]
included only at LO

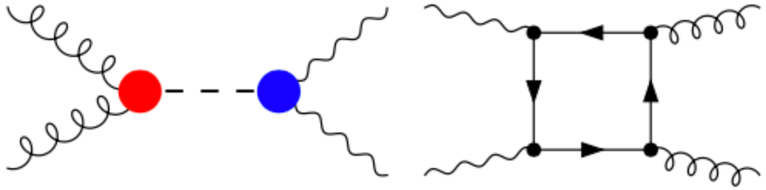
Interference effects not well investigated

Signal-background interference effects
beyond LO accuracy in QCD

this talk

Anatomy of interference contribution in diboson production

Consider on-shell Higgs-boson production in $H \to V_1V_2$ decay channel, e.g. $\gamma\gamma$ or $Z\gamma$ (ZZ and WW uninteresting for now)



$$\mathcal{M}_{gg\to V_1V_2} = \frac{\mathcal{M}_{\rm sig}}{m^2_{V_1V_2} - m_H^2 + i\Gamma_H m_H} + \mathcal{M}_{\rm bkg}$$

$$\left|\mathcal{M}_{gg\to V_1V_2}\right|^2 = \frac{|\mathcal{M}_{\rm sig}|^2}{(m^2_{V_1V_2} - m_H^2)^2 + \Gamma_H^2 m_H^2} + |\mathcal{M}_{\rm bkg}|^2 + 2{\rm Re}\left(\frac{\mathcal{M}_{\rm sig}}{m^2_{V_1V_2} - m_H^2 + i\Gamma_H m_H}\mathcal{M}^\dagger_{\rm bkg}\right)$$

Consider real and imaginary parts of amplitudes independently

$$\mathcal{M}_{sig/bkg} = {\rm Re}(\mathcal{M}_{sig/bkg}) + i\,{\rm Im}(\mathcal{M}_{sig/bkg})$$

$$\left|\mathcal{M}_{gg\to V_1V_2}\right|^2 = |S|^2 + |B|^2 + \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2} - m_H^2)^2 + \Gamma_H^2 m_H^2}\left[\boxed{(m^2_{V_1V_2} - m_H^2){\rm Re}\,I} + \boxed{\Gamma_H m_H {\rm Im}\,I}\right]$$

$${\rm Re}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig} + {\rm Im}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig}$$

$${\rm Im}\,I = {\rm Re}\mathcal{M}_{\rm bkg}{\rm Im}\mathcal{M}_{\rm sig} - {\rm Im}\mathcal{M}_{\rm bkg}{\rm Re}\mathcal{M}_{\rm sig}$$

"real-part"
of the interference

"imaginary-part"
(absorptive)
of the interference

Real and imaginary parts of interference

Real part

$$I_{\rm Re} \propto \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2}-m^2_H)^2+\Gamma^2_H m^2_H}\,(m^2_{V_1V_2}-m^2_H)\,{\rm Re}\,I$$

- Antisymmetric around the peak, does not contribute to the cross section
- unbalance of events around the Higgs peak: excess abobe/below the peak

  apparent mass shift [S.P. Martin 1208.1533; Dixon, Li 1305.3854]

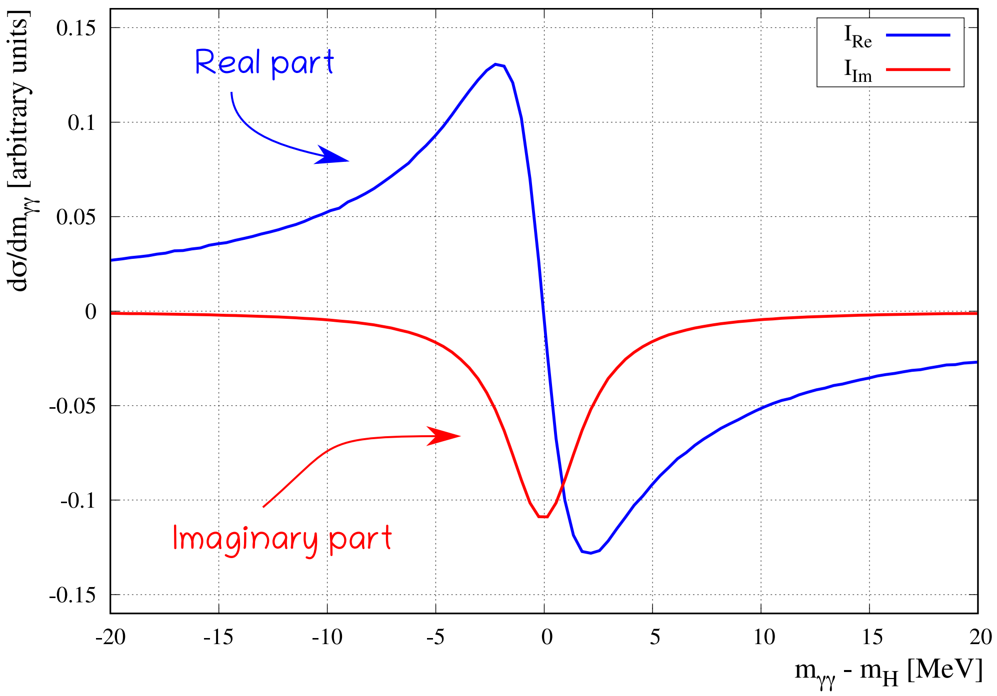
Imaginary part

$$I_{\rm Im} \propto \frac{2m^2_{V_1V_2}}{(m^2_{V_1V_2}-m^2_H)^2+\Gamma^2_H m^2_H}\,\Gamma_H m_H\,{\rm Im}\,I$$

- Symmetric around the peak, contributes to the cross section
- Relative phase of sig-bkg amplitudes is such that the interference is destructive in γγ. Zγ?

Expected impact on on-shell cross-section: few to several %

sketch borrowed from γγ case

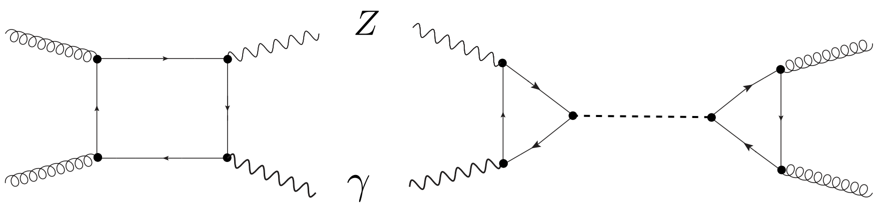


As for Zγ:

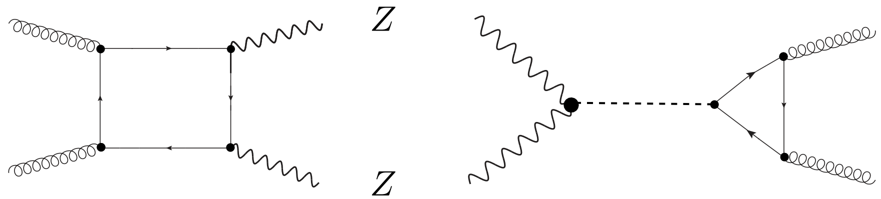
what sign does the real part have?

is the interference constructive or destructive?

Back of the envelope estimates of interference contribution



$$B_{\gamma Z} \sim \frac{g_s^2 e^2}{(4\pi)^2} \qquad S_{\gamma Z} \sim \lambda_i \lambda_f$$



$$B_{ZZ} \sim \frac{g_s^2 e^2}{(4\pi)^2} \qquad S_{ZZ} \sim \lambda_i \frac{e^2 v}{2 c_w^2 s_w^2}$$

$$\frac{S_{\gamma Z}}{S_{ZZ}} \sim \left(\frac{c_w s_w m_H}{2\pi v}\right)^2 \sim 10^{-3}$$

$$\lambda_i \sim \frac{\alpha_s}{4\pi}\frac{m_H^2}{v}$$

$$\lambda_f \sim \frac{\alpha_w}{4\pi}\frac{m_H^2}{v}$$

Naive power counting/dim analysis:

$$\frac{\sigma_{int,Z\gamma}}{\sigma_H} \sim 2\frac{\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_H^2} \sim 4\%$$

"Loop enhancement"

Interference effects unlikely to explain factor 2 disagreement with data

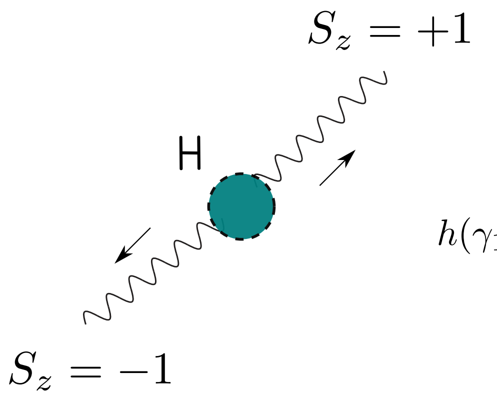
However:

1. Pattern of effects less trivial than this:
   - strong phases → absorptive part of amplitudes
   - helicity/mass considerations
2. Contributions from higher-loop diagrams
   - large NLO corrections in γγ [Dixon, Siu hep-ph/0302233]
   - x 6 larger the LO contribution

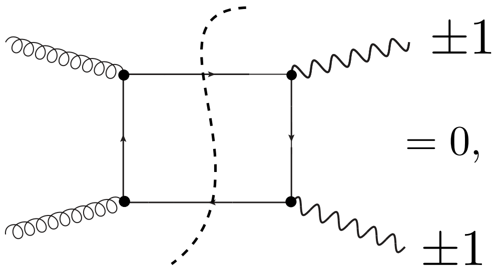
assessment of interference important
(regardless of SM-data tension)

Spin, cuts and masses: γγ vs Zγ

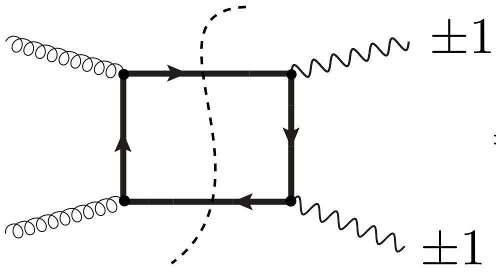
In diphoton production, contribution to cross-section effectively starts only at 2-loop



$h(\gamma_1) = h(\gamma_2) = \pm 1$

Im(A) ~ 

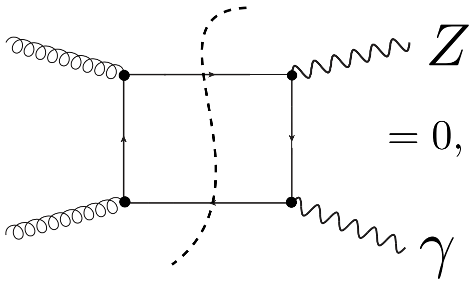
$= 0, \quad \text{for} \quad m_q = 0$

Im(A) ~ 

$\neq 0, \quad \text{for} \quad s > 4m_q^2$

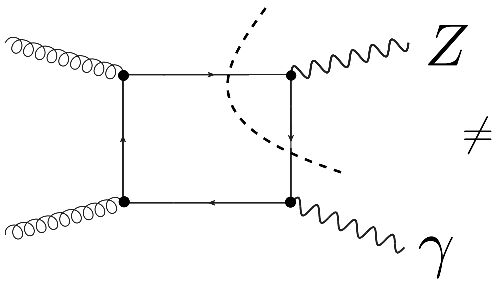
bottom effects ~
mass suppressed, $O(m_q^2/s)$

In Zγ production such helicity selection on γ does not occurr (only gg)



$= 0, \quad \text{for} \quad m_q = 0$

gg still in same-helicity state

Im(A) ~ 

$\neq 0$

cut from $q_Z^2 > 0$

absorptive part
already at LO

Dominant contributions to the interference

Pattern of interference terms non-trivial (mass effects, production, decay, background amplitudes,γ*, real radiation, partonic channels etc)

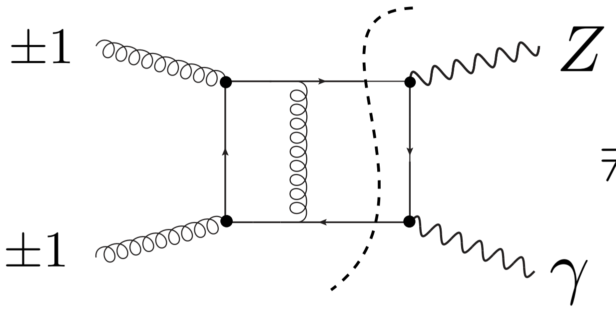
Our goal:
capture those contributions that go beyond "conventional" QCD effects and impact event yield

absorptive parts of amplitudes (strong phases)

loop corrections + light quarks on shell

Two-loop QCD corrections for $gg \to Z\gamma$ [Gehrmann, Tancredi and Weihs 1302.2630]

helicity amplitudes with loops of massless quarks

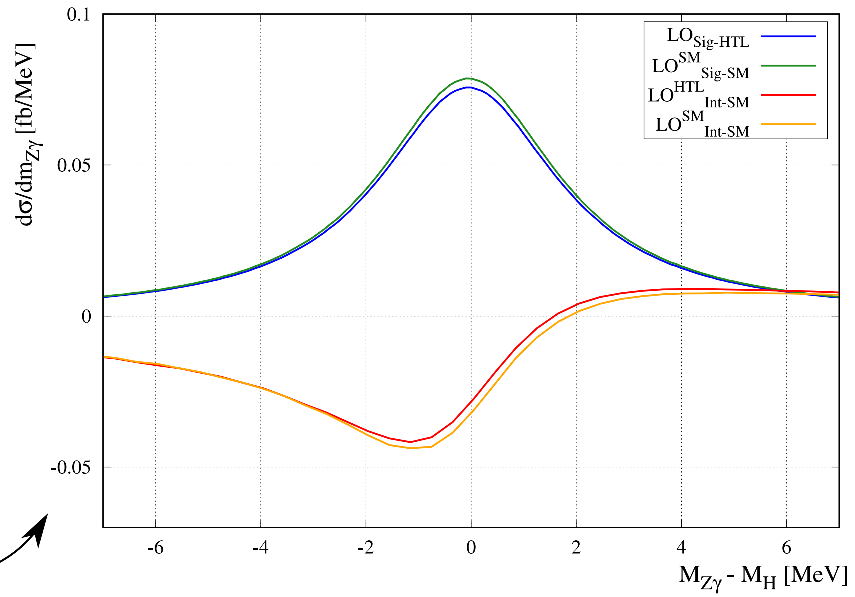


$\neq 0$

top-quark does not contribute (below threshold)

light massive quarks (b) mass suppressed in bkg

HTL vs SM with massive top and bottom in ggH



Investigate corrections beyond LO by means of so-called soft-virtual approximation

Retain all contributions from soft emissions: including virtual diagrams

(neglect impact of hard QCD radiation)

Soft-virtual approximation in a nutshell

Soft-virtual (SV) @NLO: consider only soft emissions, discard hard real contributions

The SV approximation and various improvements of it extensively adopted for Higgs predictions (colour singlet in general)

Several proposals on how to account for subleading terms

Important: process largely dominated by gg-fusion

The only process-dependent part is encoded in purely virtual contributions

Differential hadronic cross-section:

$$\mathrm{d}\sigma(\tau, y, \theta_i) = \int \mathrm{d}\xi_1 \mathrm{d}\xi_2 f_g(\xi_1, \mu_F) f_g(\xi_2, \mu_F) \delta(\tau - \xi_1\xi_2 z) \mathrm{d}\hat{\sigma}\left(z, \hat{y}, \hat{\theta}_i, \alpha_s, Q^2\right)$$

Soft limit of the partonic cross section, i.e. z→1:

$$\mathrm{d}\hat{\sigma}\left(z, \hat{y}, \hat{\theta}_i, \alpha_s, Q^2\right) \simeq \mathrm{d}\hat{\sigma}_{\mathrm{Born}}\, z\, G\left(z, \alpha_s, Q^2\right) \qquad G(z, \alpha_s) = \delta(1-z) + \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n G^{(n)}(z)$$

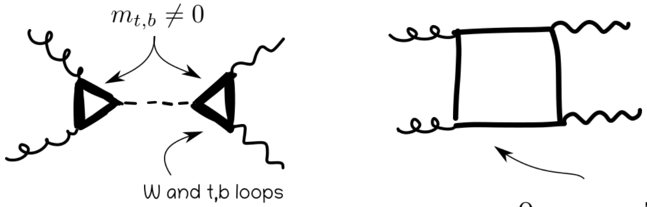
In soft-virtual approximation:

$$G^{(n)}(z) = c_0^{(n)} \delta(1-z) + \sum_{k=1}^{2n-1} c_k^{(n)} \mathcal{D}_k(z)$$

process-dependent part

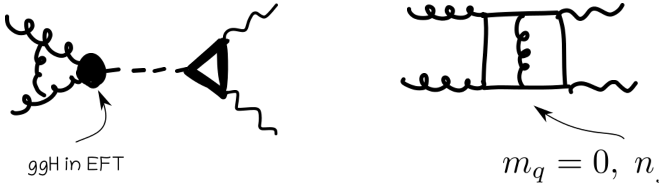
Setup of the calculation (main ingredients)

LO:



$m_q = 0,\ n_f = 5$

NLO$_{sv}$:



$m_q = 0,\ n_f = 5$

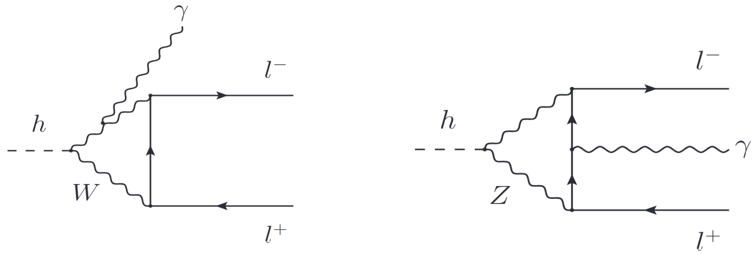
Helicity amplitudes:
allow for fully spin-correlated Z decay

arbitrary cuts on leptonic final states

1. Work in pole-approximation: resonant Z-boson

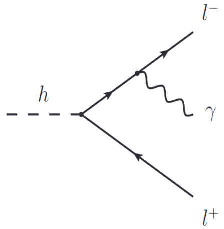
   guaranteed by invariant mass cut on e^+e^-

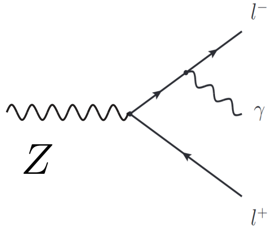
   Effectively discard contributions such as:

   - 

   - Interference terms $\gamma\gamma^*$ - γZ: $O(\Gamma_Z/m_Z) \sim 2.7\%$

2. Discard contributions with γ radiation off leptons

   - In signal component: 

     suppressed by smallness of Yukawa
   - In background component: 

     suppressed by Higgs resonance region

Setup of the calculation @NLO$_{SV}$

We focus on the scenario $Z \to e^- e^+$

Selection criteria for electrons/photon in $H \to Z\gamma$ inspired by ATLAS analysis [ATLAS 2005.05382]

$$\sqrt{s} = 13.6\,\mathrm{TeV}$$

PDF set: NNPDF31_nlo_as_0118

Choice of scale: $\mu_F = \mu_R = m_{Z\gamma}/2$

Fiducial cuts:

- $p_{T,i} > 10\,\mathrm{GeV} \quad i \in \{e^-, e^+, \gamma\}$
- $50\,\mathrm{GeV} < m_{e^-e^+} < 101\,\mathrm{GeV}$
- $|y_{e^\pm}| < 2.47$
- $|y_\gamma| < 2.37$

We have investigated also a more inclusive setup (no p_T or y cuts)

Similar conclusions, mainly a normalisation contribution to the line-shpe

naive soft-virtual in general does poorly @NLO: several recipes to tweak and improve it

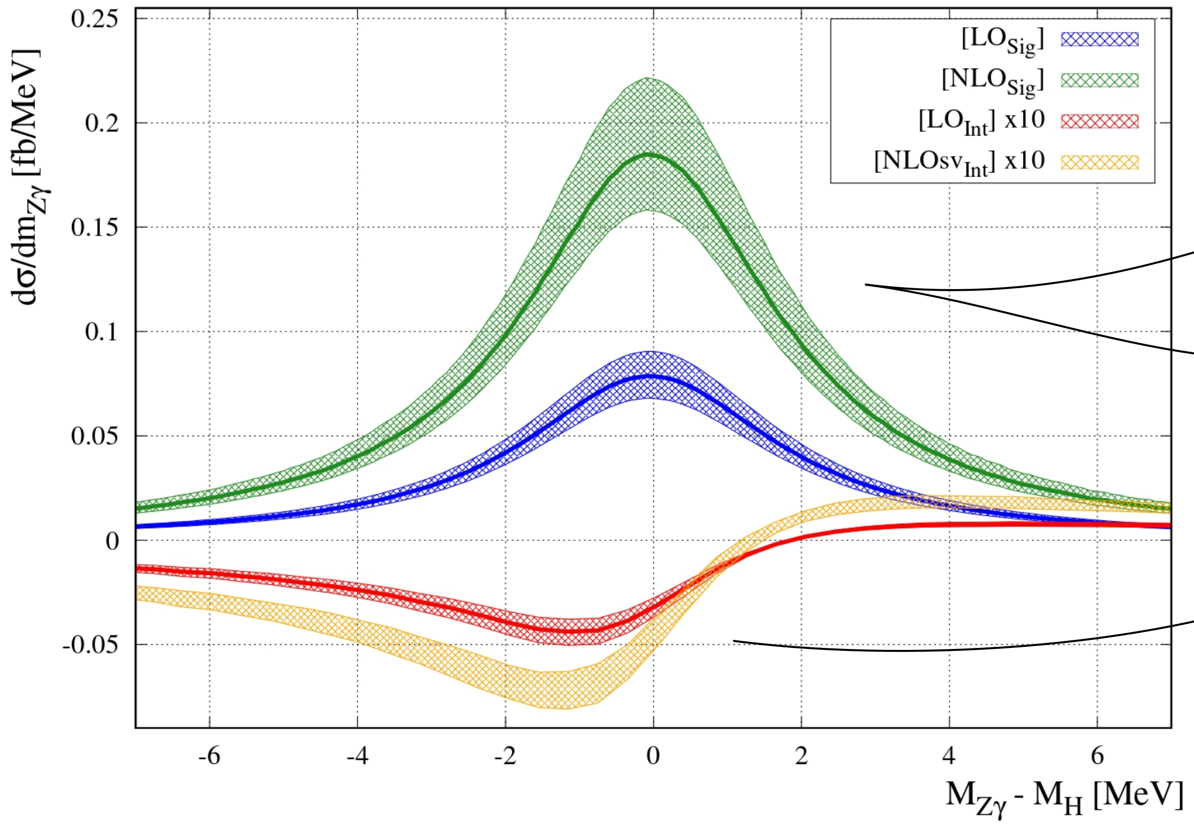
to provide a more reliable estimation of the uncertainties related to SV calculation: adopt alternative approach and compare

NLO$_{SV}$': we follow the strategy in

[Ball, Bonvini, Forte, Marzani, Ridolfi 1303.3590] [Bonvini et al 1304.3053]

$$\mathcal{D}_i(z) \to \mathcal{D}_i(z) + (2-3z+2z^2)\frac{\ln^i \frac{1-z}{\sqrt{z}}}{1-z} - \frac{\ln^i(1-z)}{1-z}$$

Signal-background interference beyond LO



signal process treated exactly at NLO QCD (in HTL)
i.e. real + virtual

uncertainty on signal process: conventional factor-2 variation on top of nominal scale choice

uncertainty band in interference: spread between two different SV approaches
(scale-variation bands accidentally small)

When restricting Zγ invariant mass to a very narrow window

$$\sigma_{\mathrm{Sig}}^{\mathrm{NLO}} = 1.207^{+20\%}_{-15\%}\ \mathrm{fb} \qquad \sigma_{\mathrm{Int}}^{\mathrm{NLO_{SV}}} = -0.0344^{+12\%}_{-12\%}\ \mathrm{fb}$$

Destructive interference:

- O(-4%) at LO
- O(-3%) at NLO QCD

K-factor in signal larger than in interference

Very well below the SM/data tension

Summary and outlook

- 3.4σ evidence of $H\to Z\gamma$: ATLAS + CMS combination. Tension with SM prediction: $\mu = 2.2 \pm 0.7$

- As more data will be accumulated the tension might be washed out

  most likely: statistical fluctuation

- Even so: accurate SM predictions could help understanding intricate pattern of effects

  signal-background interference effects modify event yield

  effects beyond LO: $\mathcal{O}(-3\%)$ destructive interference

  very far from SM/data tension

Outlook:

- Improved/refined picture of sig/bkg interference:

  full NLO corrections from hard QCD radiation

  assessment of $\gamma\gamma^*$ - $Z\gamma$ interference terms

  mass effects (bottom)

  contribution from other partonic channels (e.g. qg)

will put predictions on a more solid ground

very unlikely that the picture will dramatically change

In the meantime.....
we await with excitment the accumulation of more LHC data