

On the robustness of the indirect Higgs width determination

Panagiotis Stylianou

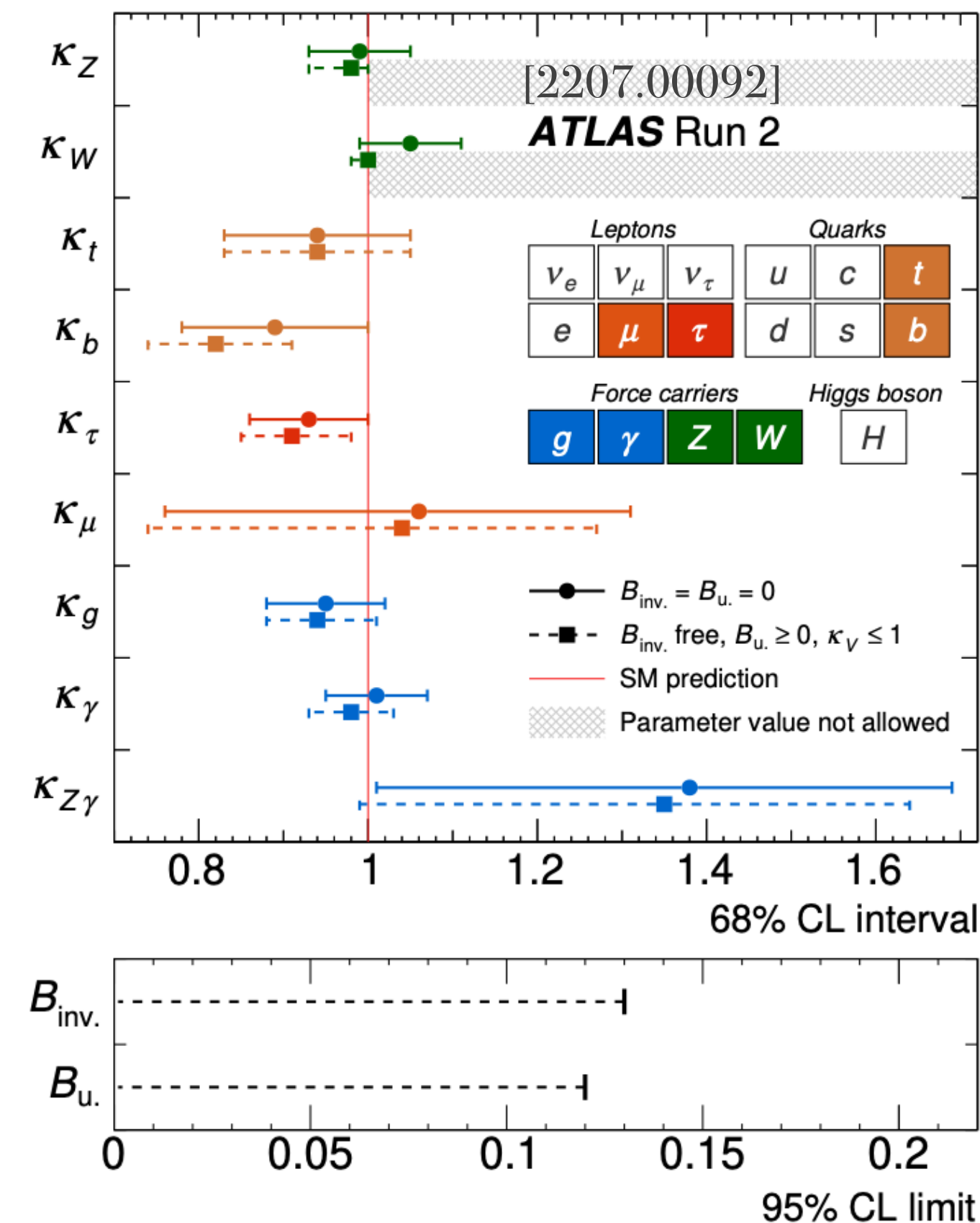
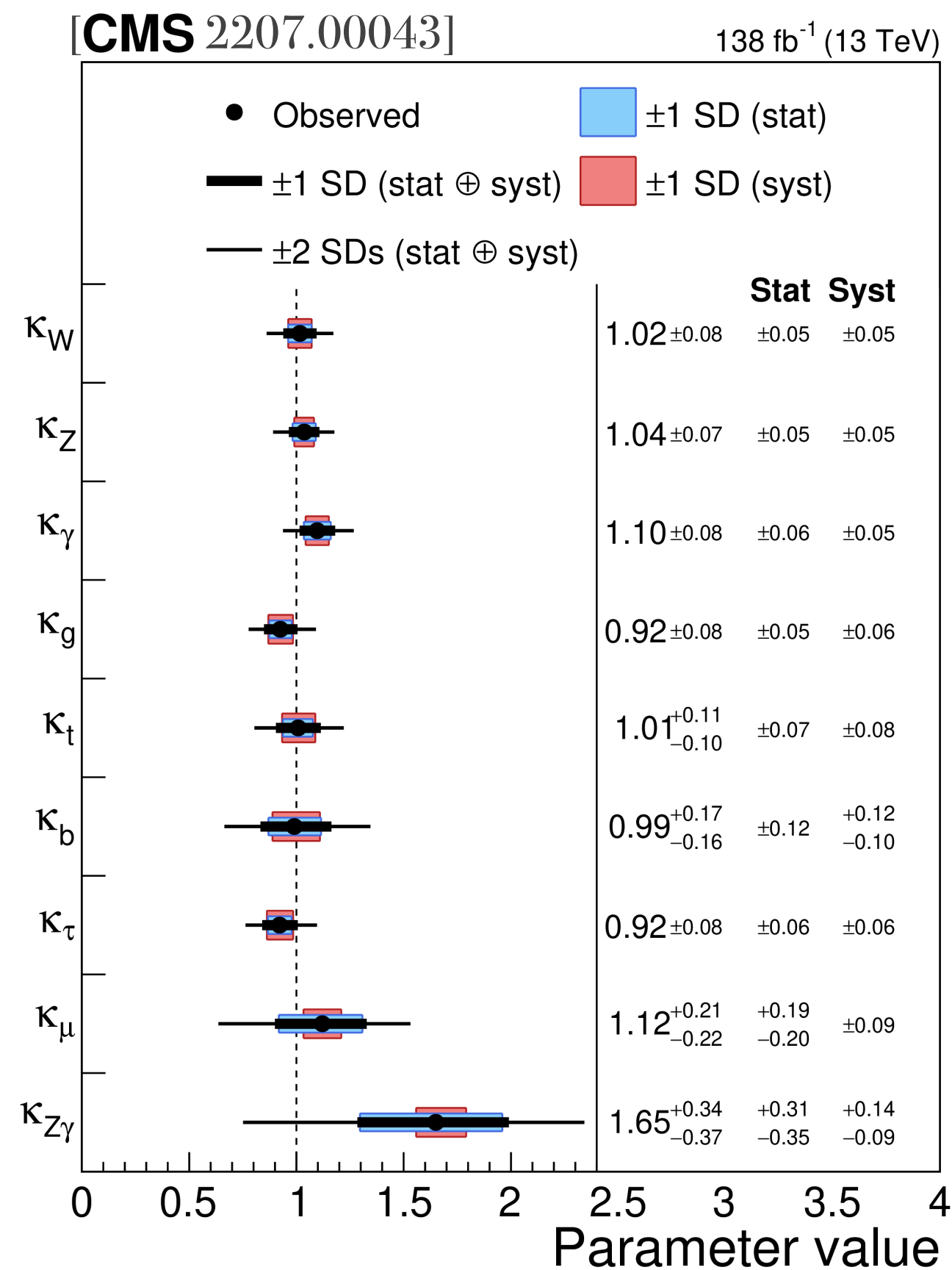
Work in collaboration with Georg Weiglein



30 January 2025

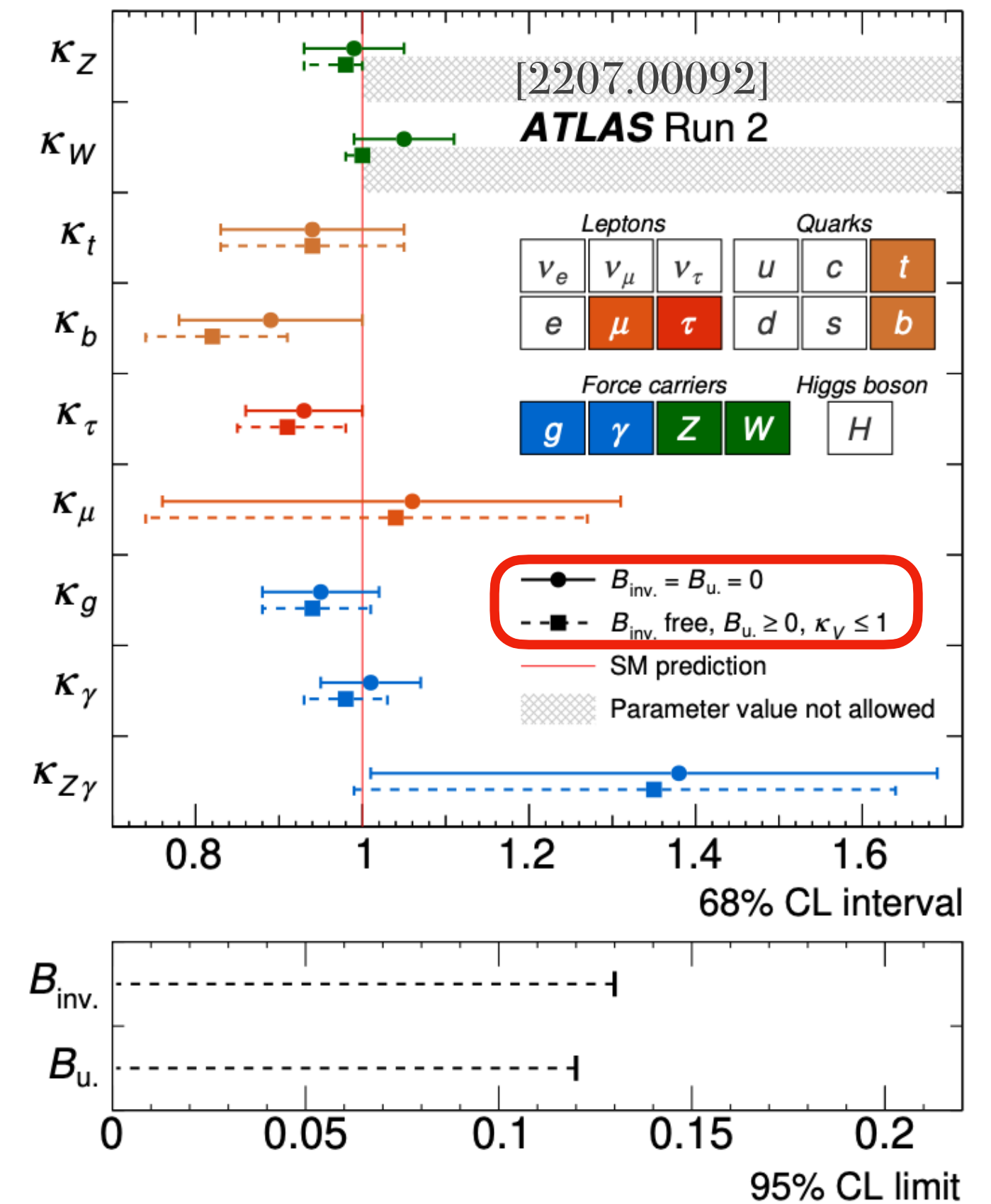
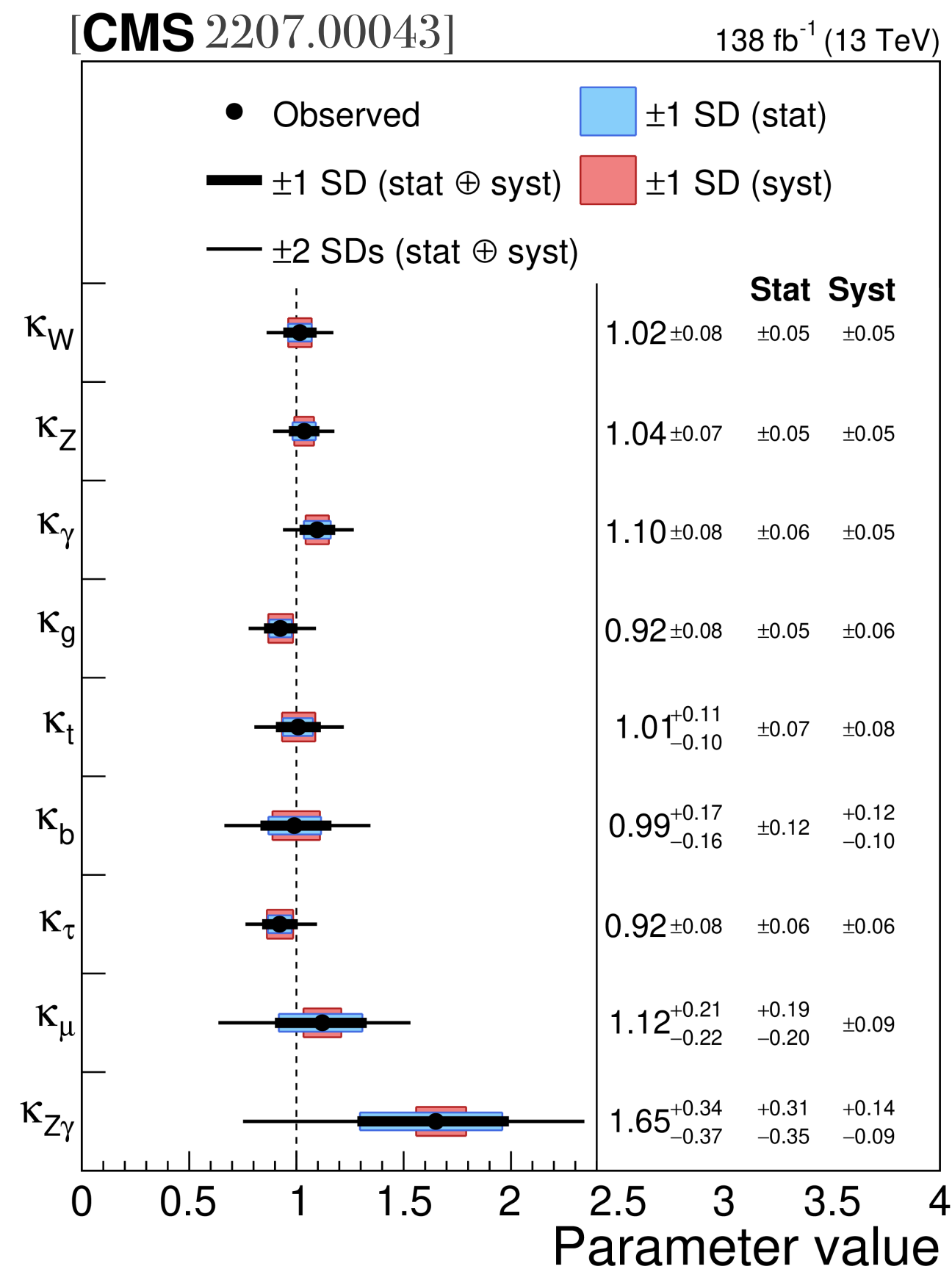
Motivation

- Measuring the couplings of the 125-GeV Higgs boson to SM particles → one of the main goals of LHC
- But the couplings are not directly accessible, experiments measure signal strengths
- When Higgs bosons are produced on-shell the signal strength depends on the total decay width of the Higgs



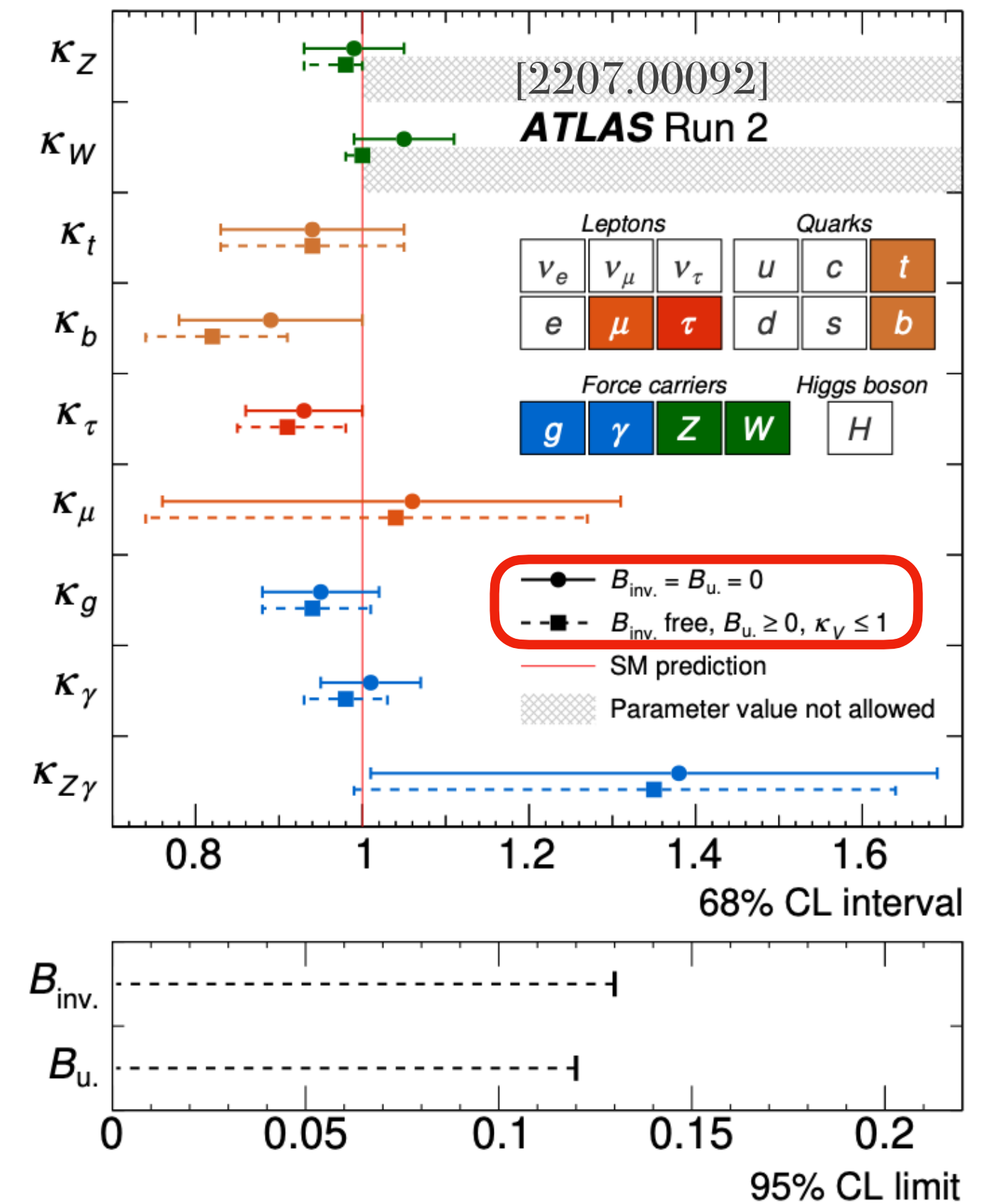
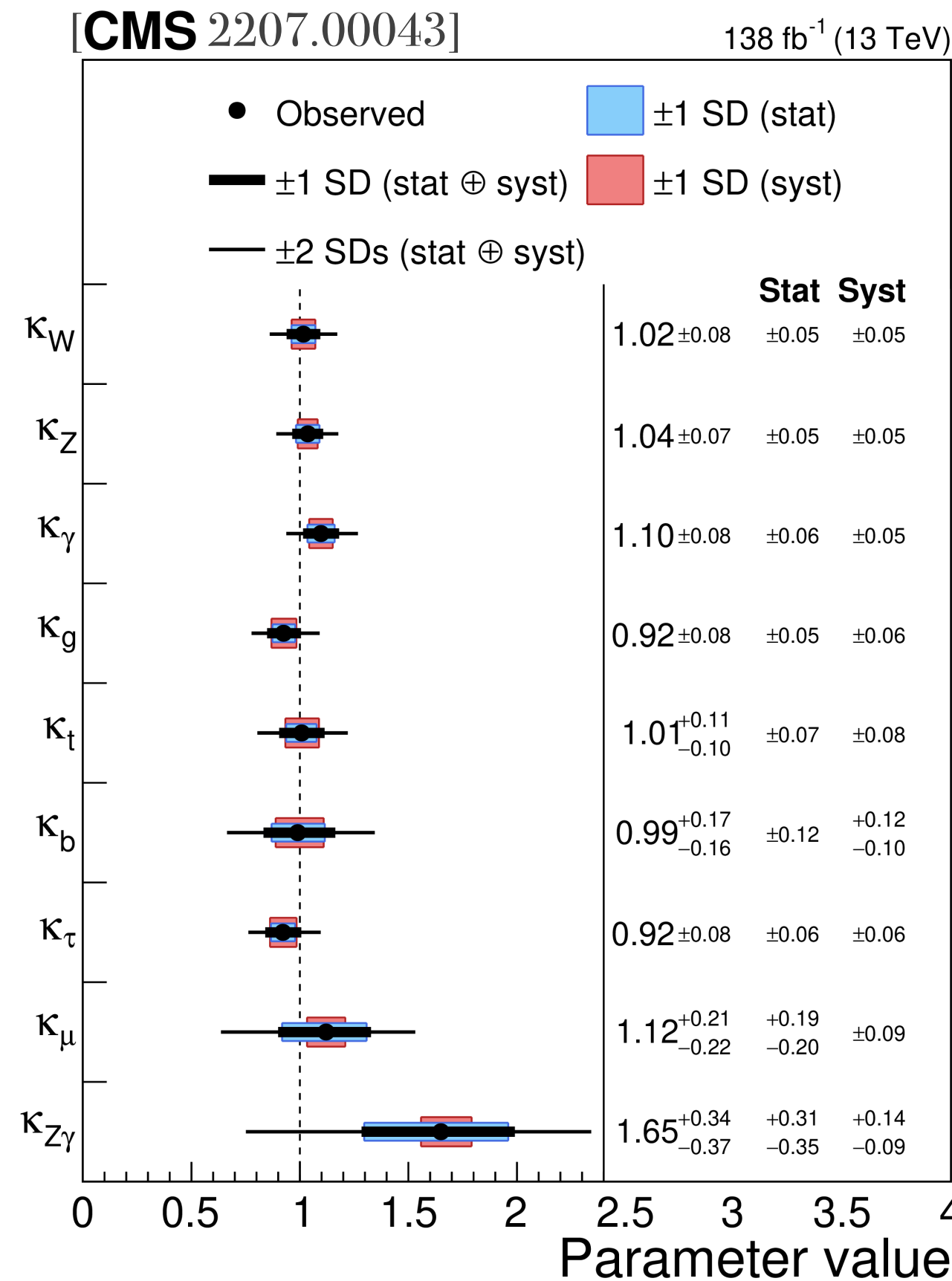
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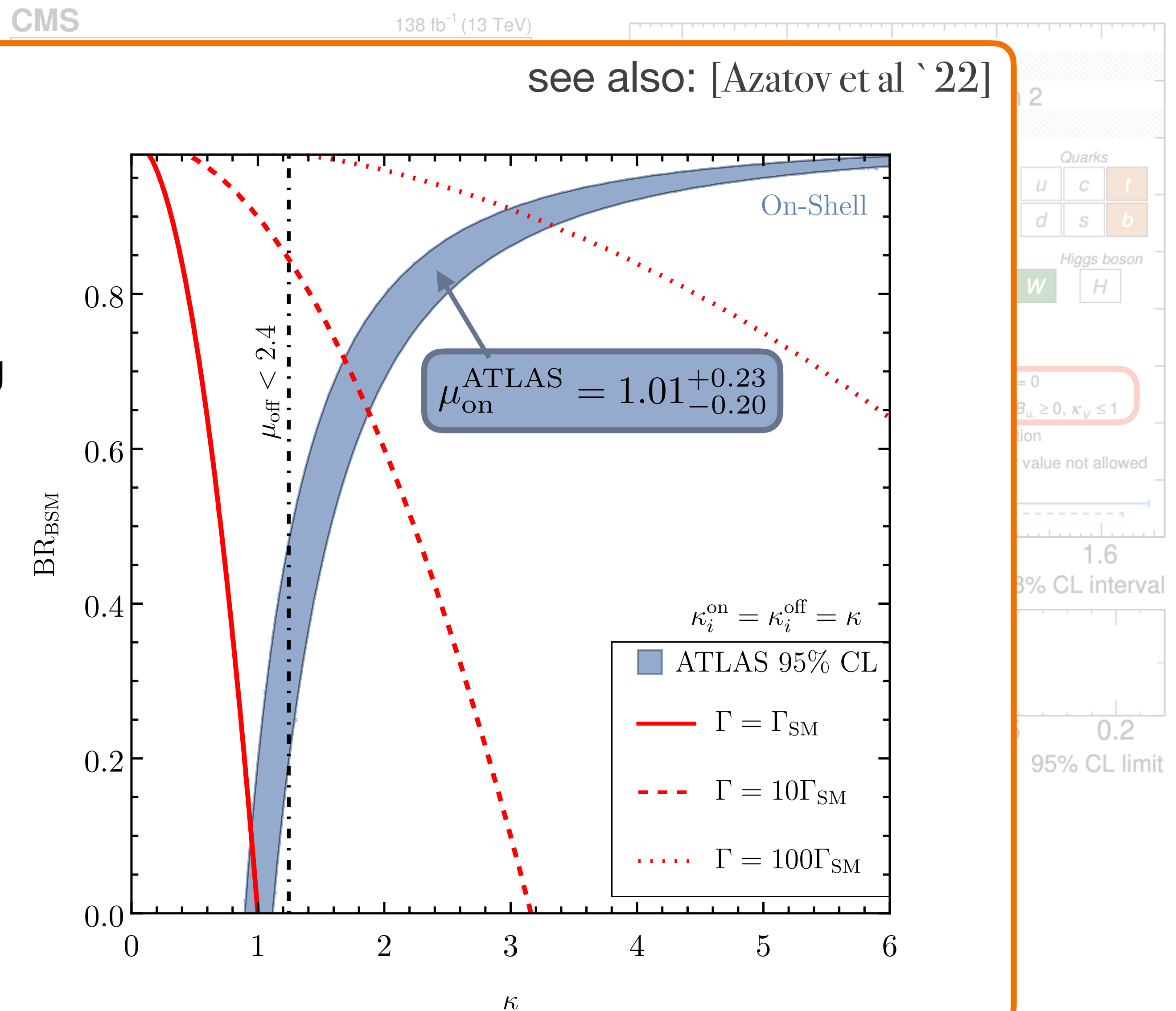
$$\mu_{\text{on}}(YY \rightarrow H \rightarrow XX) = \frac{\sigma(YY \rightarrow H) \text{BR}(H \rightarrow XX)}{\sigma^{\text{SM}}(YY \rightarrow H) \text{BR}^{\text{SM}}(H \rightarrow XX)} = \frac{\kappa_Y^2 \kappa_X^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

Motivation

- Assuming universal Higgs coupling modifiers κ and $\mu_{\text{on}} \sim 1$

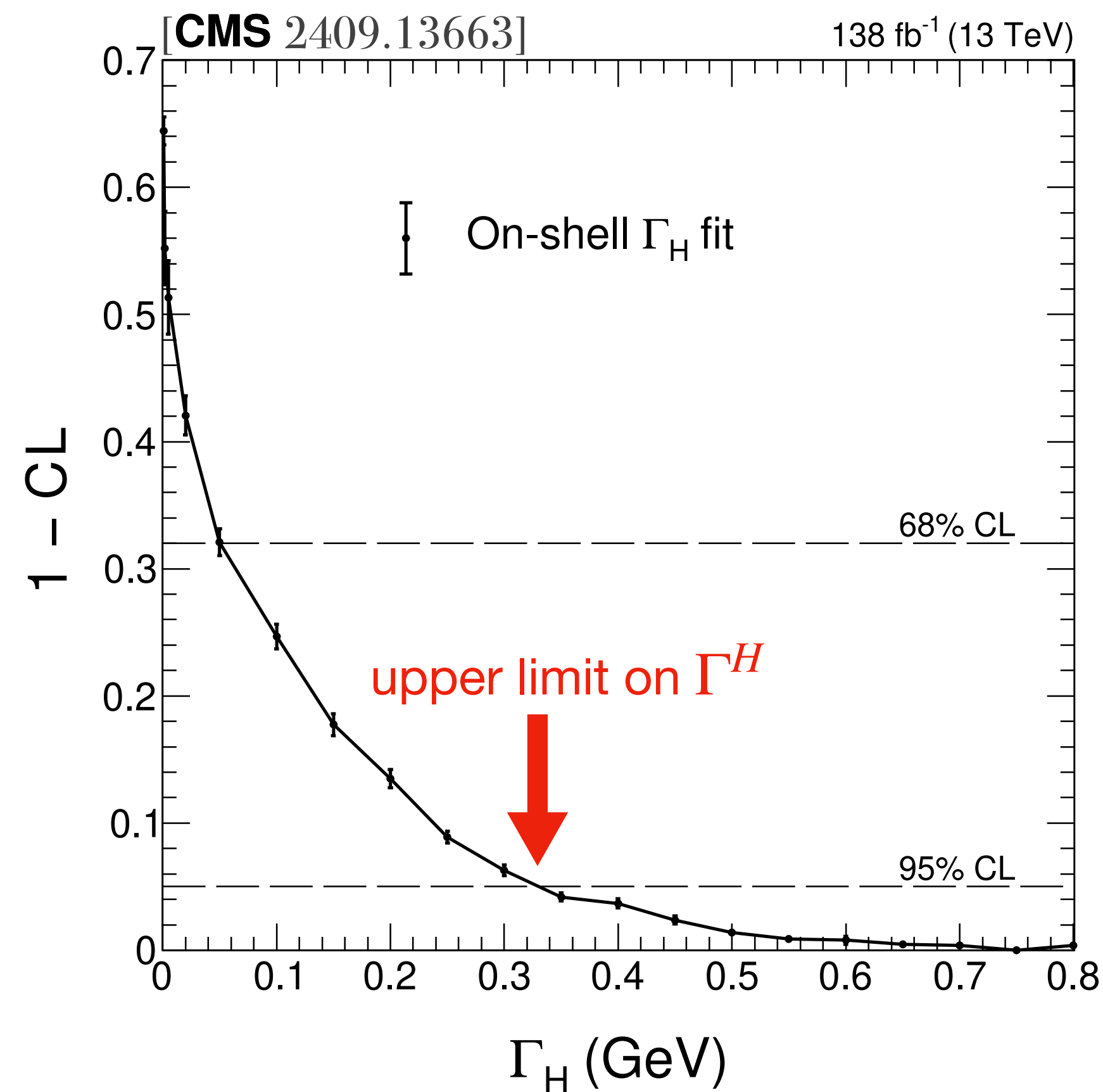
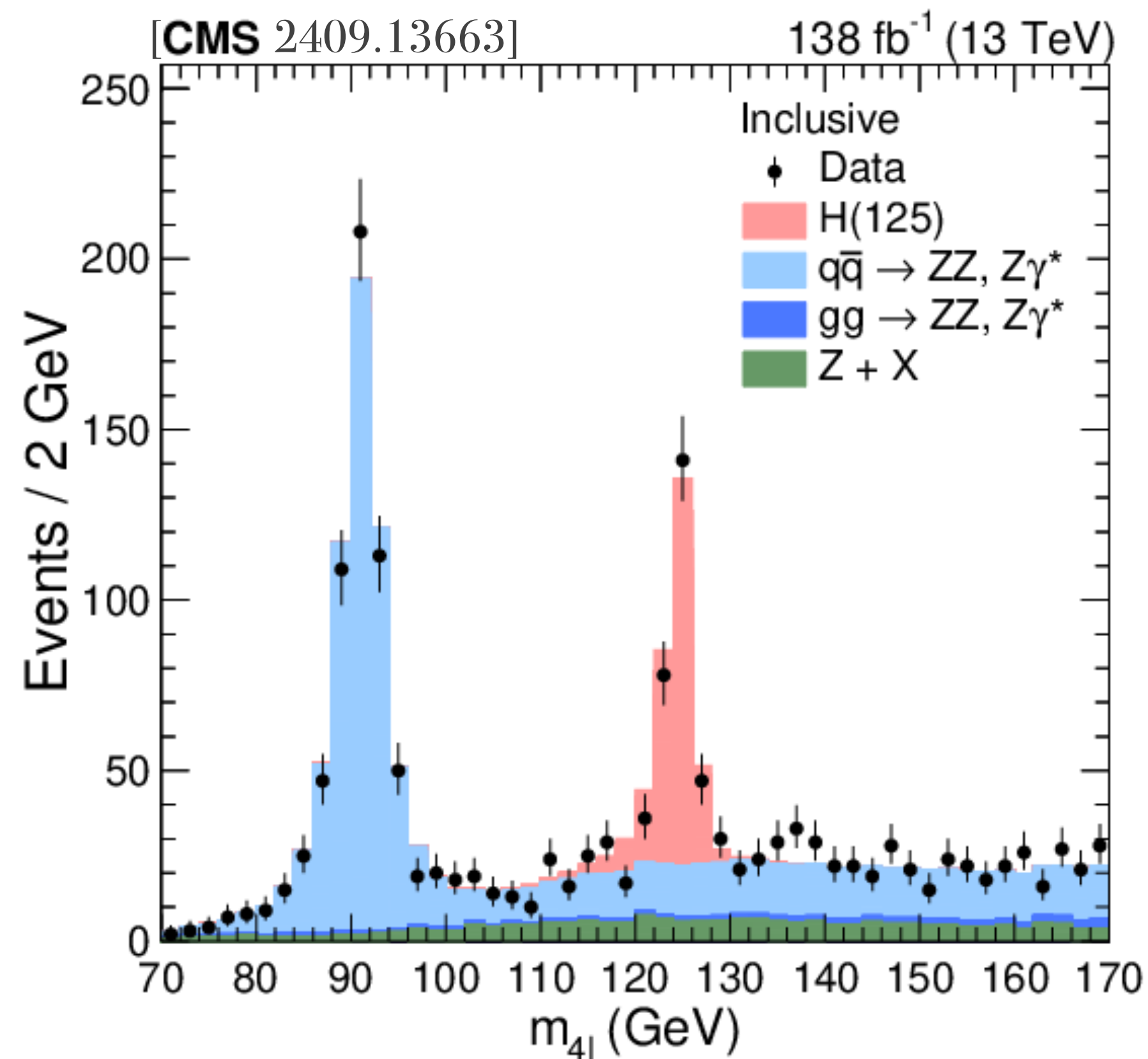
$$\text{BR}_{\text{BSM}} = \frac{\kappa^2 - 1}{\kappa^2}$$

$\Rightarrow$ **blind direction**



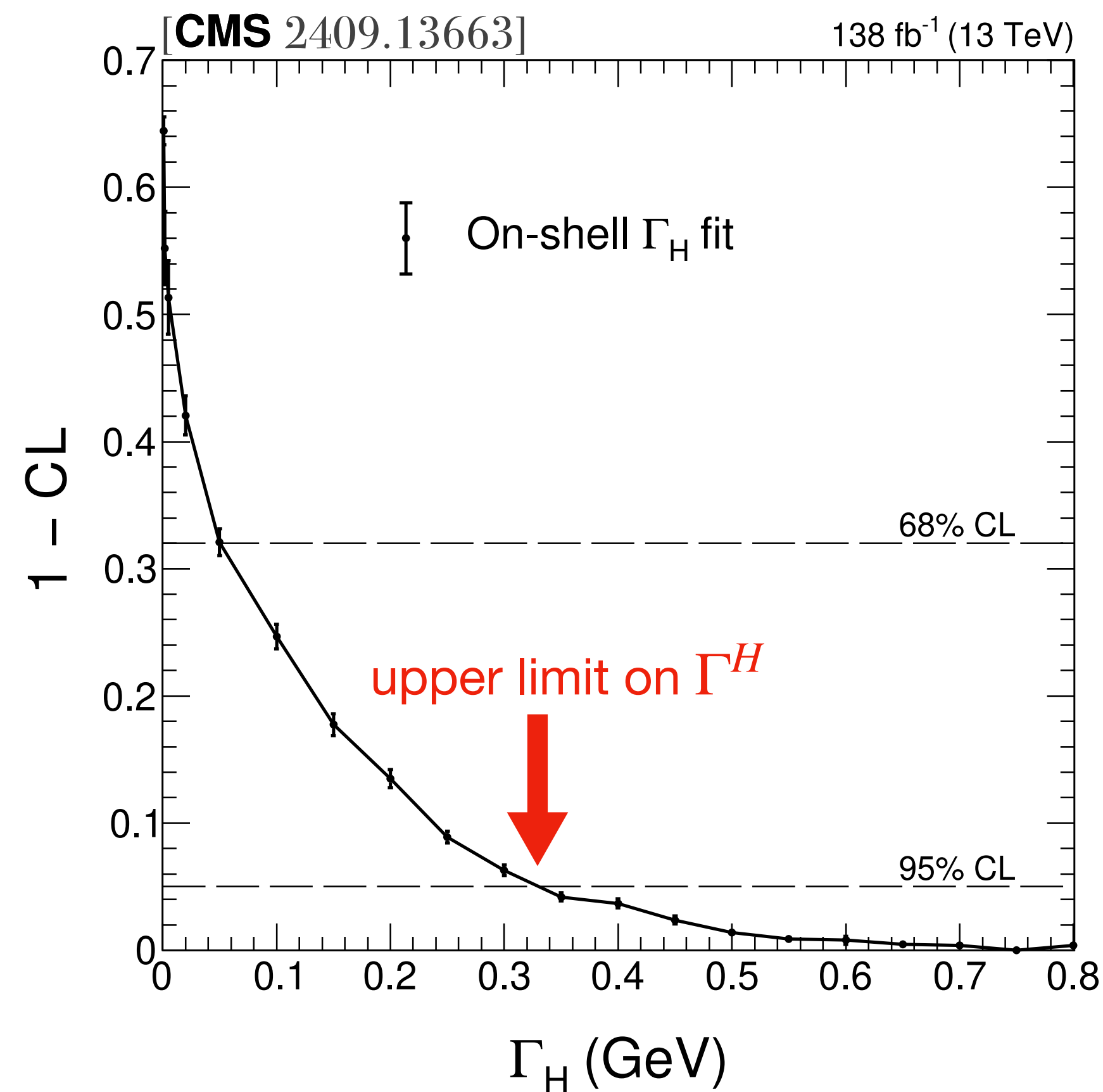
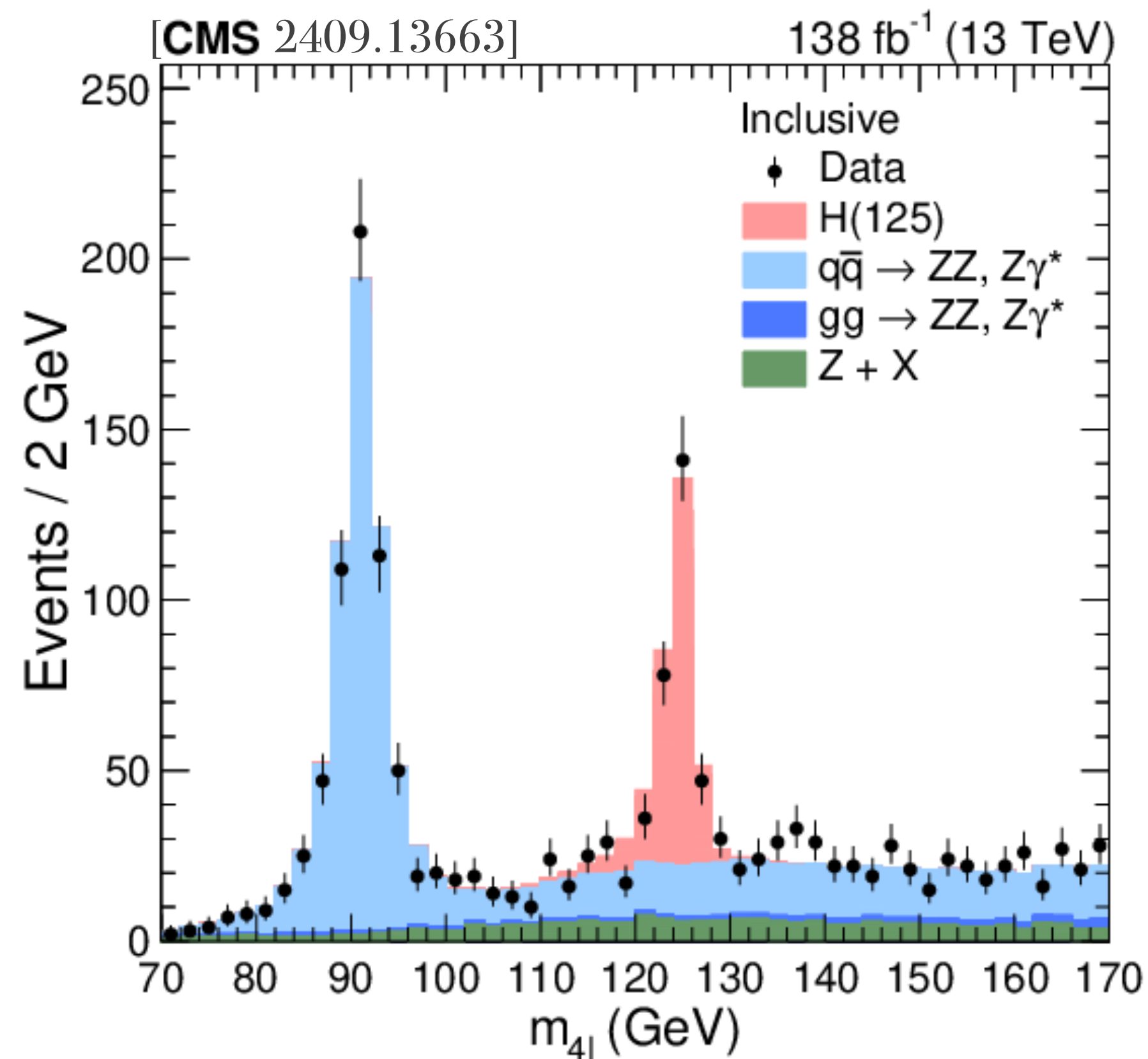
Direct measurement of the Higgs width

- SM prediction for the Higgs width: $\Gamma^H = 4.1 \text{ MeV}$ [CERN Yellow Reports V2]
- CMS upper limit on Higgs width in the on-shell $gg \rightarrow H \rightarrow ZZ^*$ channel at 95 % : $\Gamma^H < 330 \text{ MeV}$

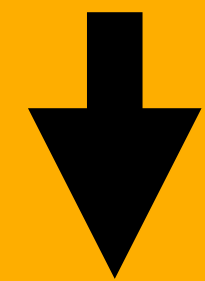


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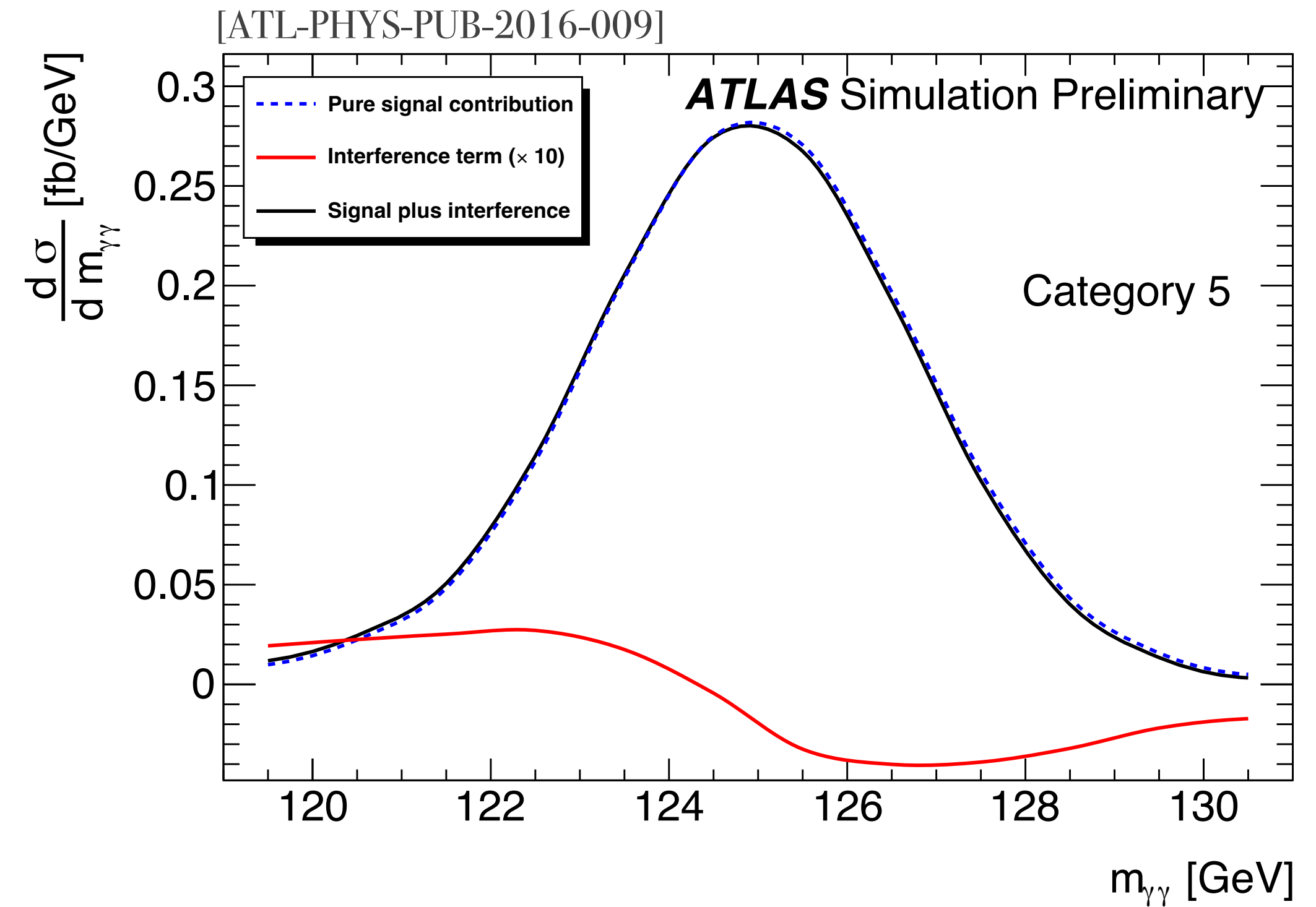
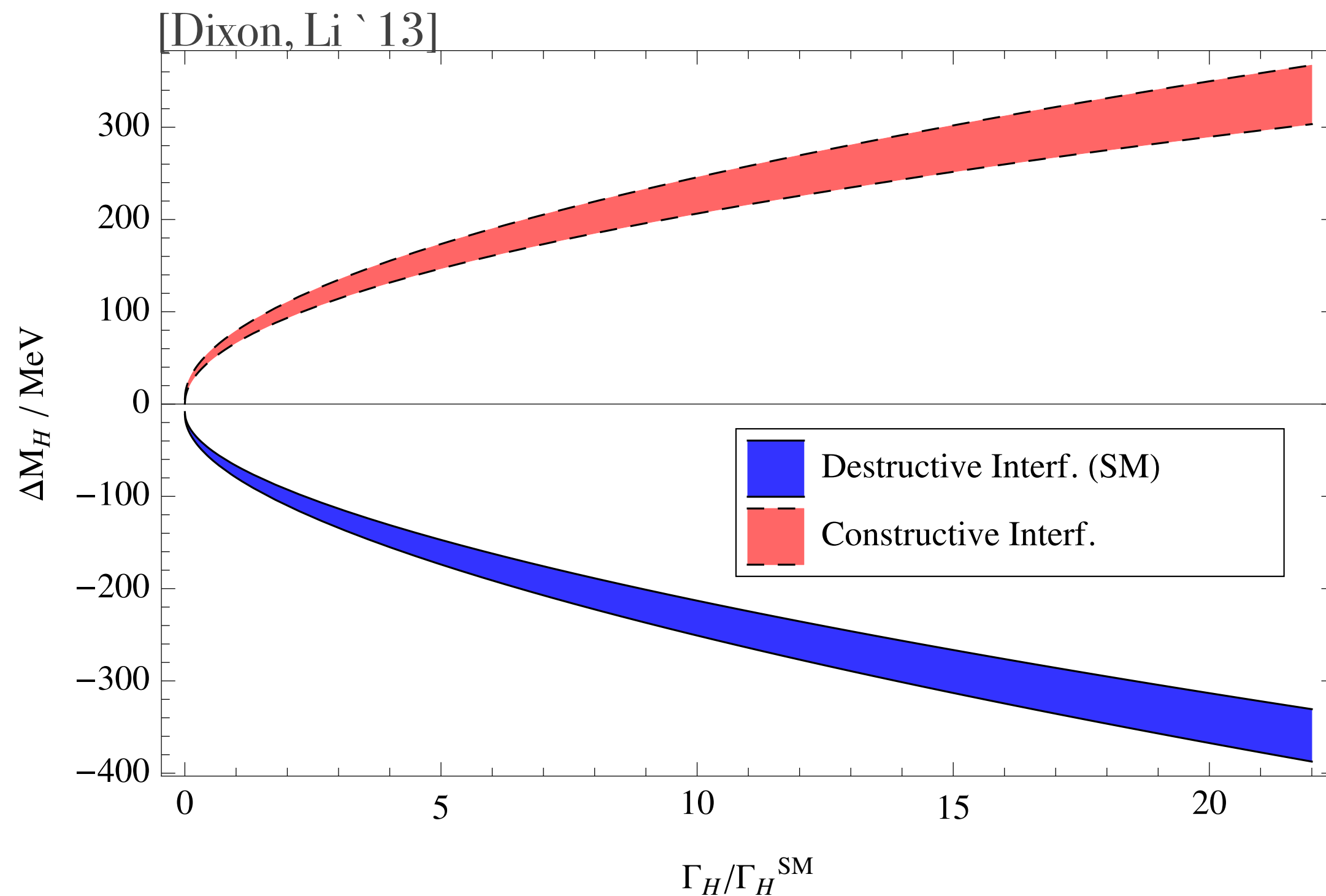
Direct limits are orders of magnitude weaker than SM prediction



Indirect measurements

Indirect width measurement: mass shift

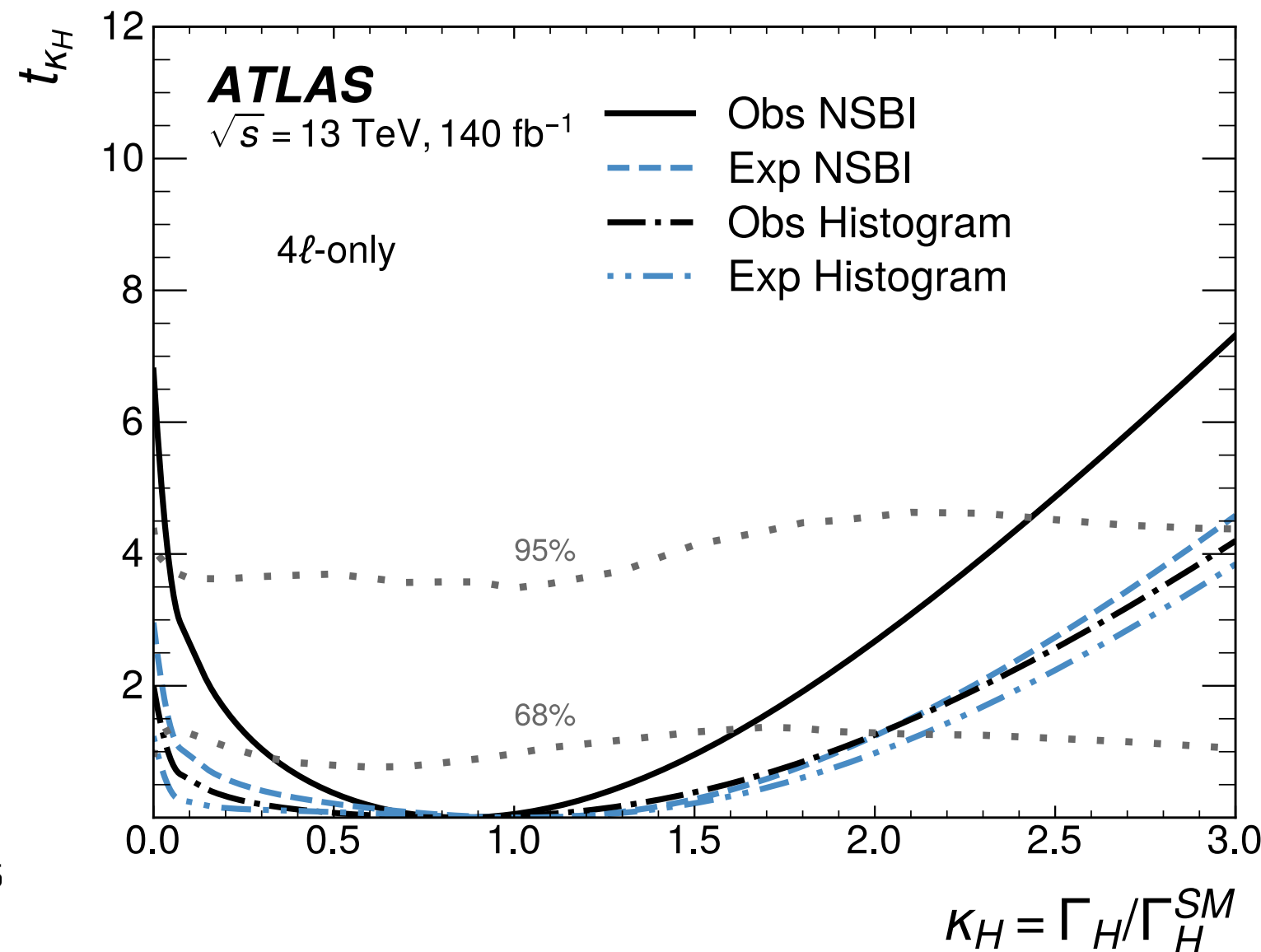
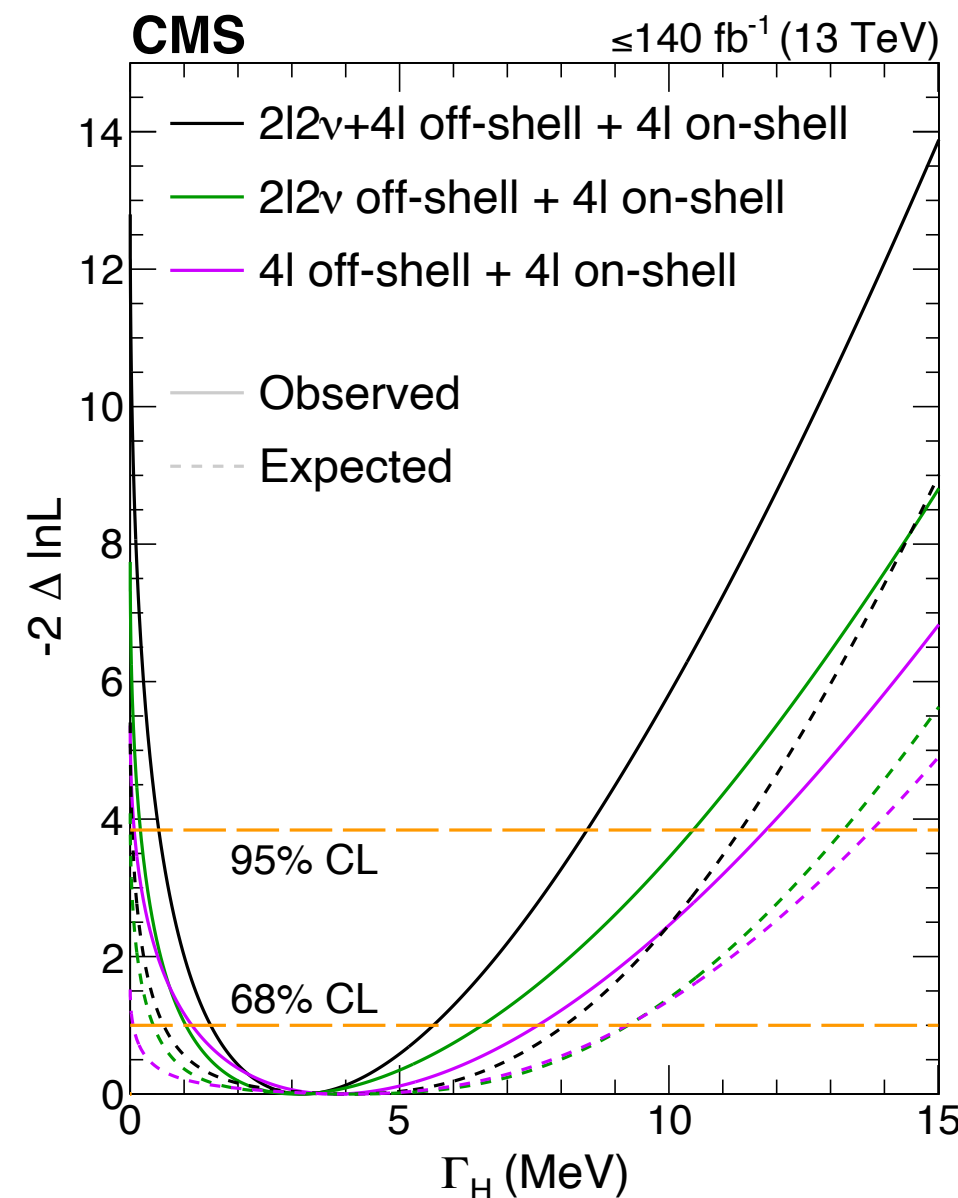
- Large interference between $gg \rightarrow H \rightarrow \gamma\gamma$ and background $gg \rightarrow \gamma\gamma$ creates a mass shift in $m_{\gamma\gamma}$
- Can compare the peaks in $\gamma\gamma$ and 4ℓ channels and use the shift to probe Γ_H [Dixon, Li '13]
- Method limited by current mass resolution



Indirect off-shell width measurement

- Off-shell cross section of $gg \rightarrow H \rightarrow VV$ enhanced by threshold effects [Kauer, Passarino `12]
- Can be exploited to measure the Higgs width Γ_H [Caola, Melnikov `13]
- Requires assumption $\kappa_{i,\text{off}} = \kappa_{i,\text{on}}$
- Measured by CMS & ATLAS [CMS 2202.06923]
[ATLAS 2304.01532]
[ATLAS 2412.01548]

$$\begin{aligned}\mu_{\text{on}}(gg \rightarrow H \rightarrow ZZ) &= \frac{\sigma(gg \rightarrow H)\text{BR}(H \rightarrow ZZ \rightarrow 4\ell)}{\sigma_{\text{SM}}(gg \rightarrow H)\text{BR}_{\text{SM}}(H \rightarrow ZZ \rightarrow 4\ell)} \\ &= \frac{\kappa_{g,\text{on}}^2 \kappa_{Z,\text{on}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}} \\ \mu_{\text{off}}(gg \rightarrow H \rightarrow ZZ) &= \frac{\sigma(gg \rightarrow H \rightarrow ZZ)}{\sigma_{\text{SM}}(gg \rightarrow H \rightarrow ZZ)} \\ &= \kappa_{g,\text{off}}^2 \kappa_{Z,\text{off}}^2\end{aligned}$$



conservative ATLAS

95% CL limits:

$$\mu_{\text{off}} < 2.4 \quad \Gamma_H / \Gamma_H^{\text{SM}} < 2.5$$

Off-shell region:

$$m_{ZZ} > 220 \text{ GeV}$$

Indirect off-shell width measurement

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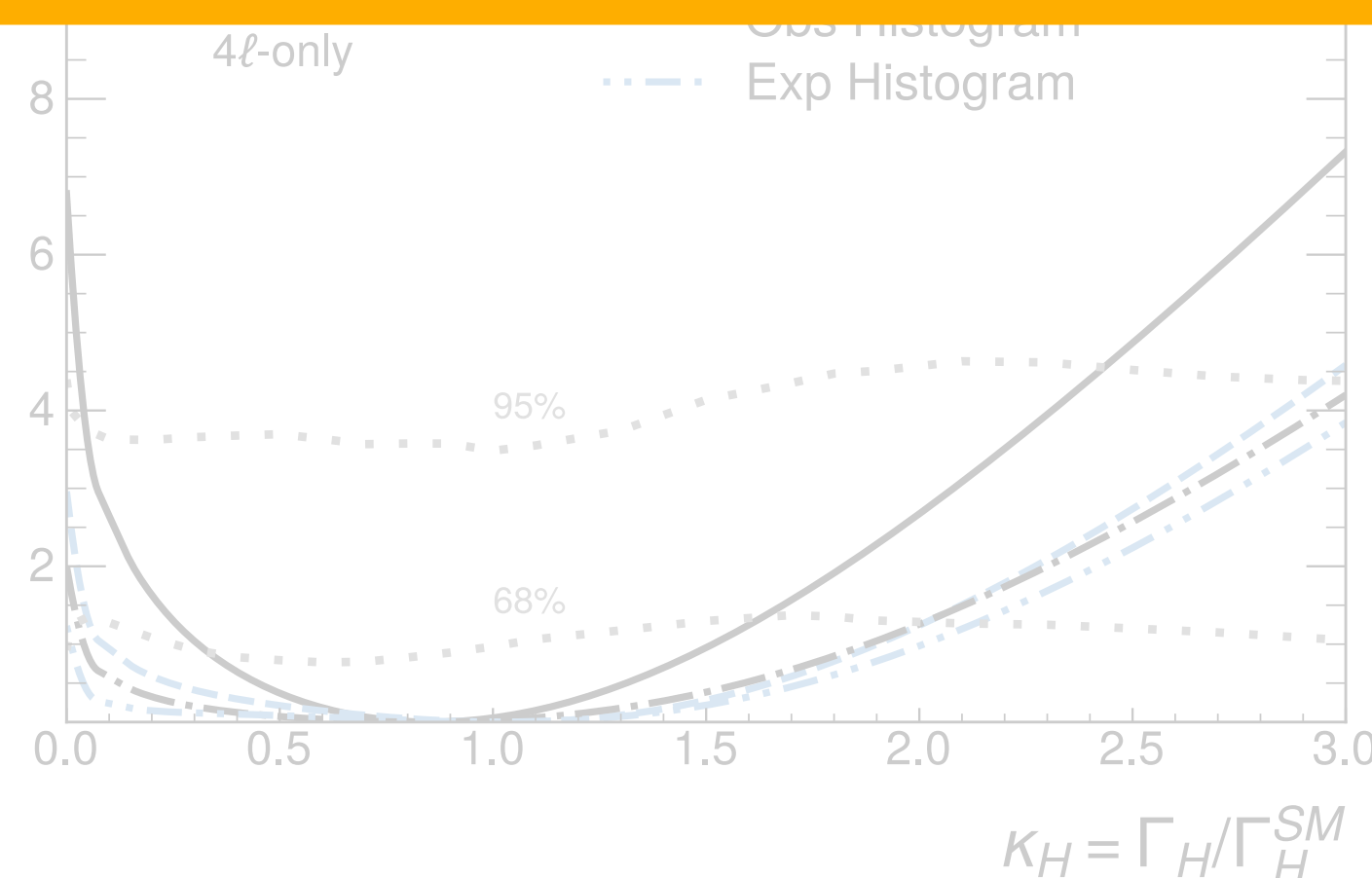
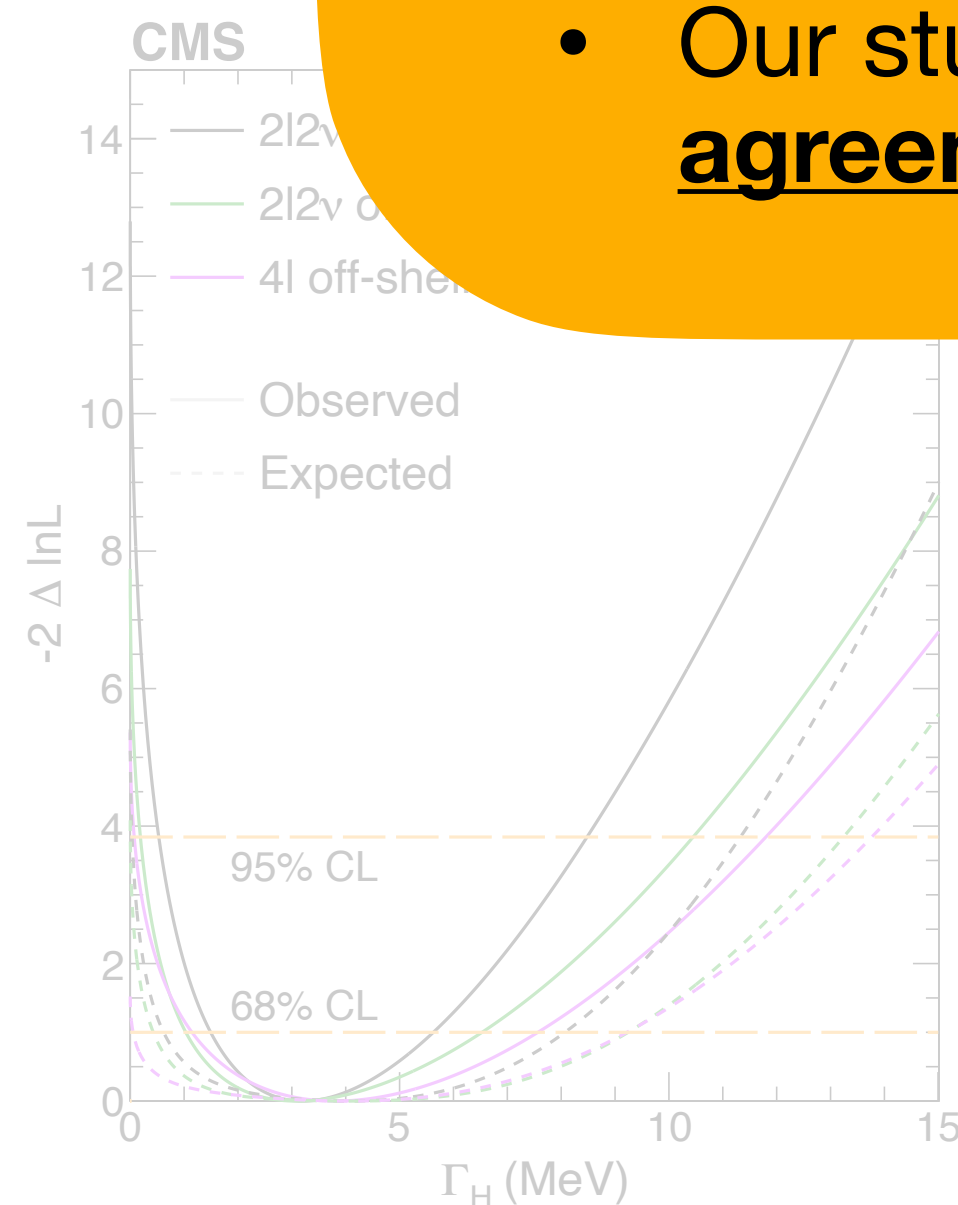
$$\mu_{\text{off}}(gg \rightarrow H \rightarrow ZZ) = \frac{\sigma(gg \rightarrow H \rightarrow ZZ)}{\sigma(gg \rightarrow H \rightarrow ZZ)}$$

[Logan `14]

[Englert, Soreq, Spannowsky `14]

[Gonçalves, Han, Mukhopadhyay `18]

- Various studies for BSM in off-shell region, e.g
- Our study: **Can we have a sizeable exotic/undetected Higgs width but in agreement with current off-shell measurements?**



$$\mu_{\text{off}} < 2.4 \quad \Gamma_H / \Gamma_H^{\text{SM}} < 2.5$$

$$m_{ZZ} > 220 \text{ GeV}$$

Relaxing the indirect width measurement assumption

- Focus on off-shell $gg \rightarrow H \rightarrow ZZ$ with only top loop $\implies$ **relevant Higgs couplings:** κ_t, κ_Z
- To allow for a larger Higgs width we need to **decrease** the off-shell rate

$$\mu_{\text{on}} \simeq \frac{\kappa_t^2 \kappa_Z^2}{\underbrace{\Gamma_H / \Gamma_H^{\text{SM}}}} \simeq 1$$

Enhanced from exotic/undetected width

$$\mu_{\text{off}} \simeq \left(\kappa_t^2 \kappa_Z^2 + \text{off-shell effects} \right) \leq 2.4$$

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- Allow deviations on κ_t, κ_Z and try to reduce off-shell rate by introducing scalars:

➡ Propagating BSM scalar $gg \rightarrow S \rightarrow ZZ$

➡ Modification of the Higgs gluon-fusion $gg \rightarrow H$ due to a BSM coloured scalar

➡ Modification the Higgs propagator with a scalar-singlet loop contribution

} one-loop level

Propagating Scalar Singlet in the ZZ channel

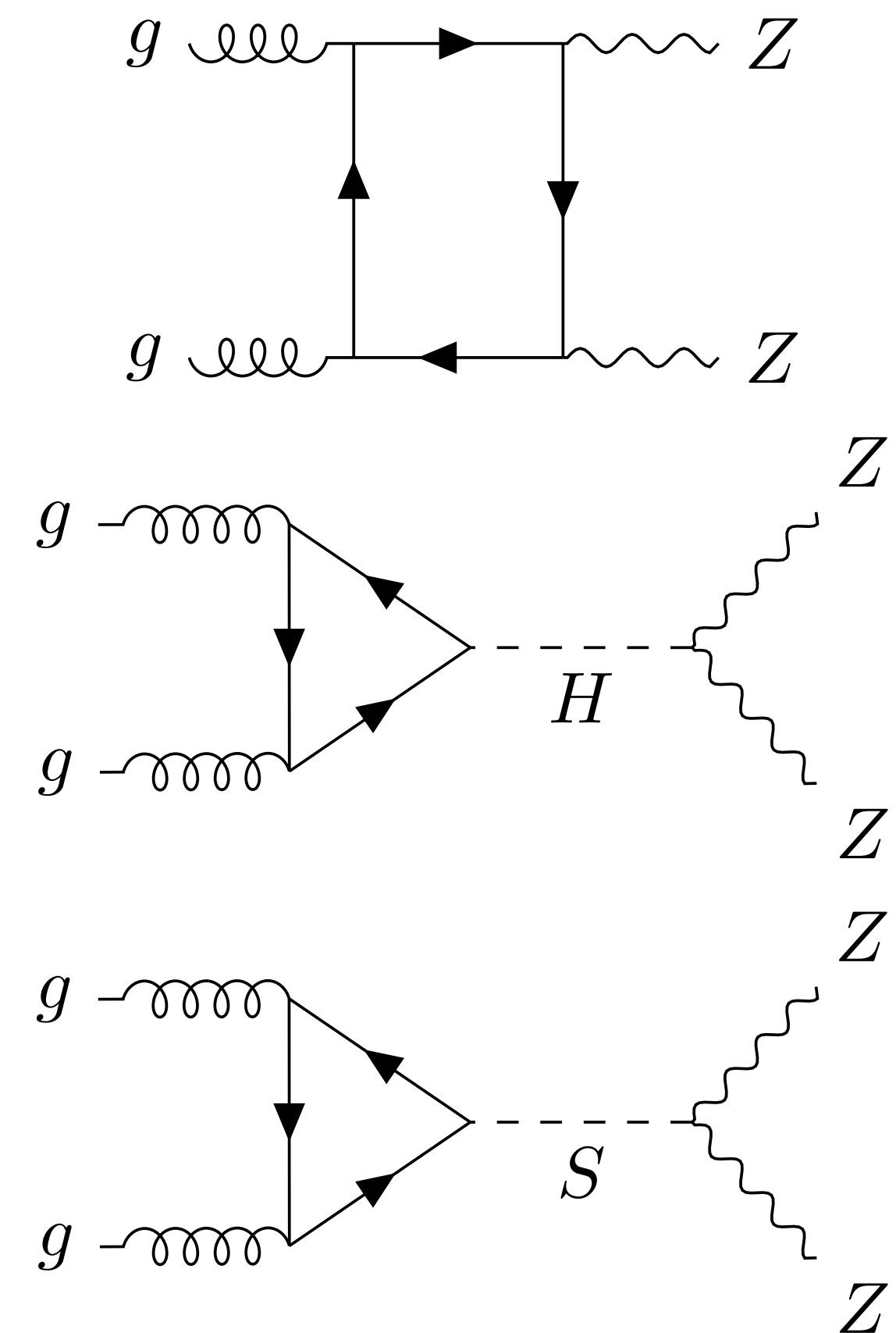
- Simple extension with a scalar singlet coupled to top-quarks and Z boson:

$$\mathcal{L} \supset -C_{Stt} \frac{y_t}{\sqrt{2}} \bar{t} S t + C_{SZZ} \frac{e^2 v}{4c_W^2 s_W^2} Z_\mu Z^\mu S$$

- Unitarity of $t\bar{t} \rightarrow ZZ$ channel requires the sum rule: [Logan '14]

$$\kappa_t \kappa_Z + C_{Stt} C_{SZZ} = 1$$

- Model implemented with FeynRules and NLOCT for simulations with MadGraph5_aMC@NLO



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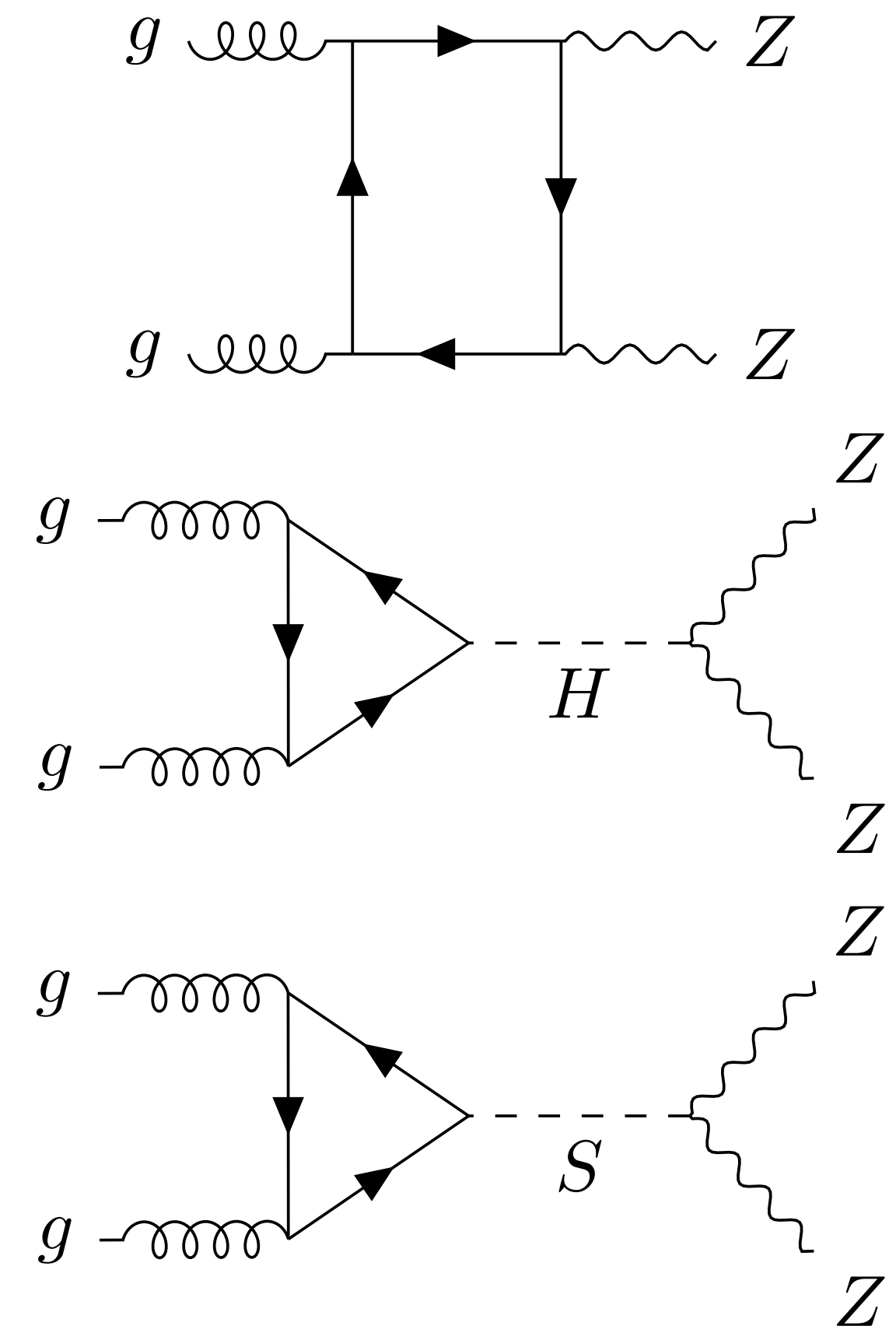
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$$\begin{aligned} d\sigma_{gg \rightarrow ZZ}(\kappa_t \kappa_Z, C_{Stt} C_{SZZ}) = & \\ & d\sigma_{(0,0)} + \kappa_t \kappa_Z d\sigma_{(2,0)} + \kappa_t^2 \kappa_Z^2 d\sigma_{(4,0)} \\ & + C_{Stt} C_{SZZ} d\sigma_{(0,2)} + \kappa_t \kappa_Z C_{Stt} C_{SZZ} d\sigma_{(2,2)} \\ & + C_{Stt}^2 C_{SZZ}^2 d\sigma_{(0,4)} \end{aligned}$$

**Parameterised
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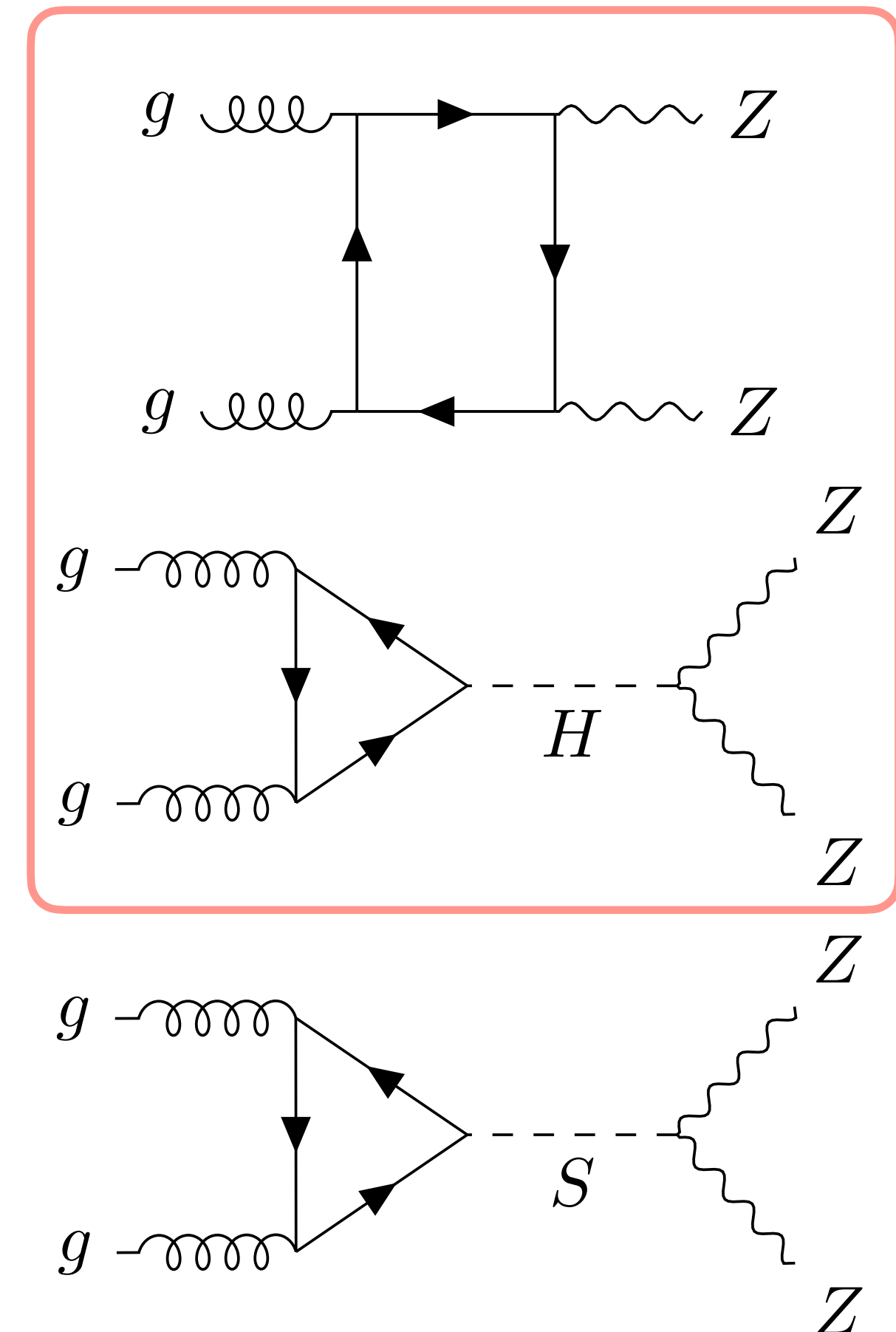
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SM with coupling modifiers



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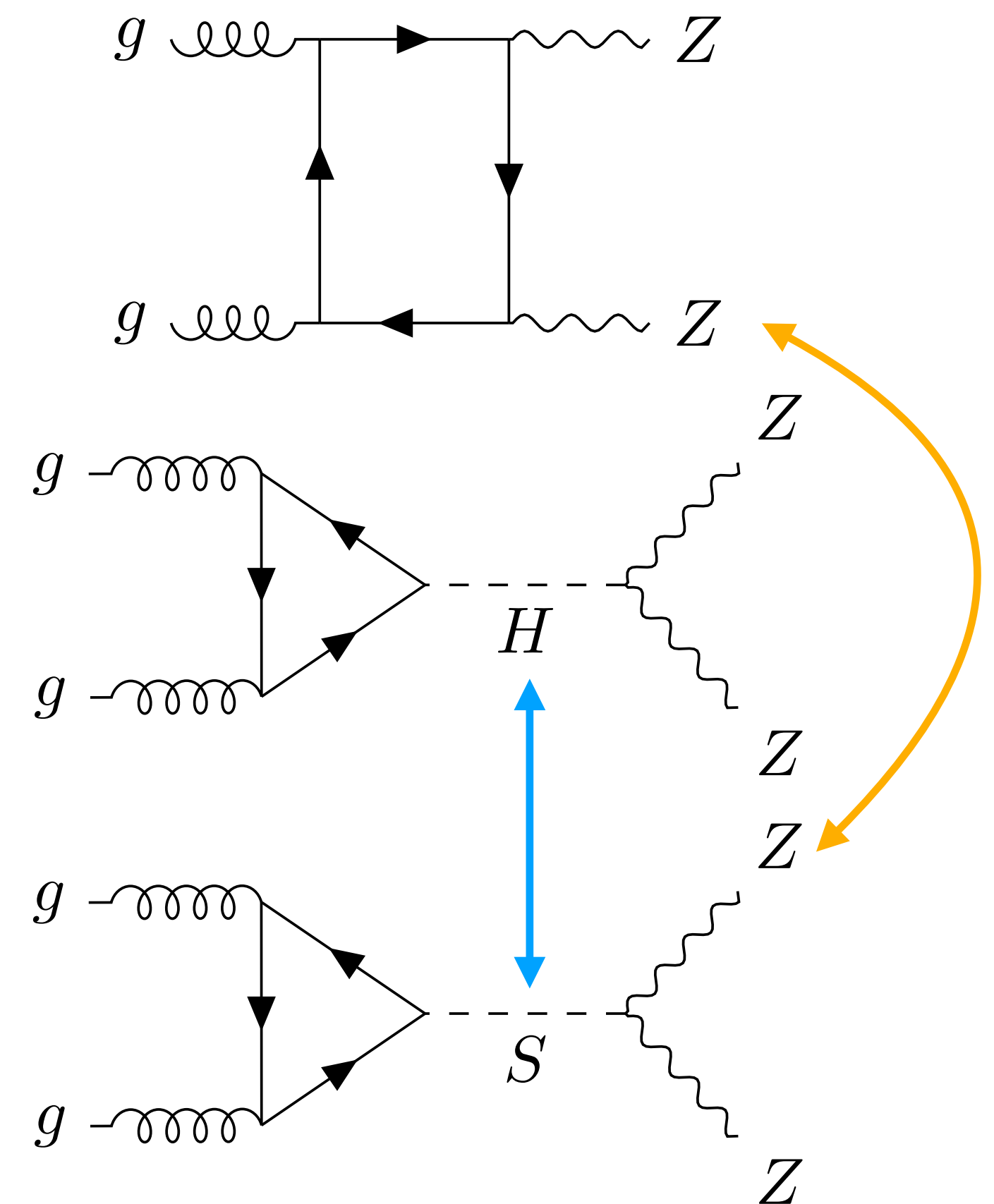
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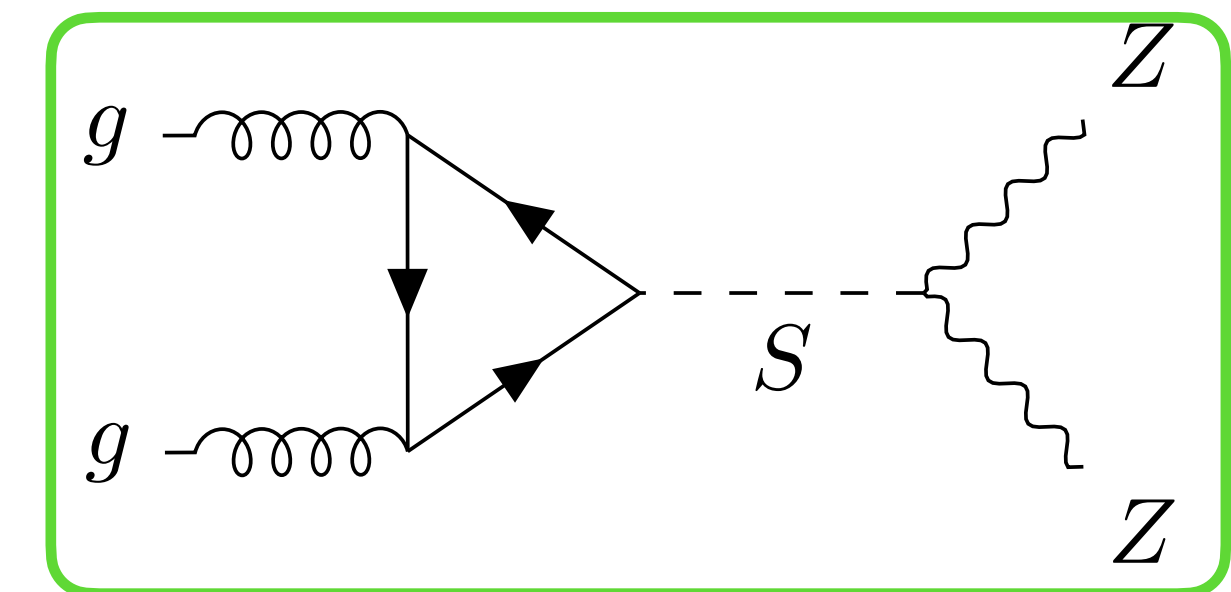
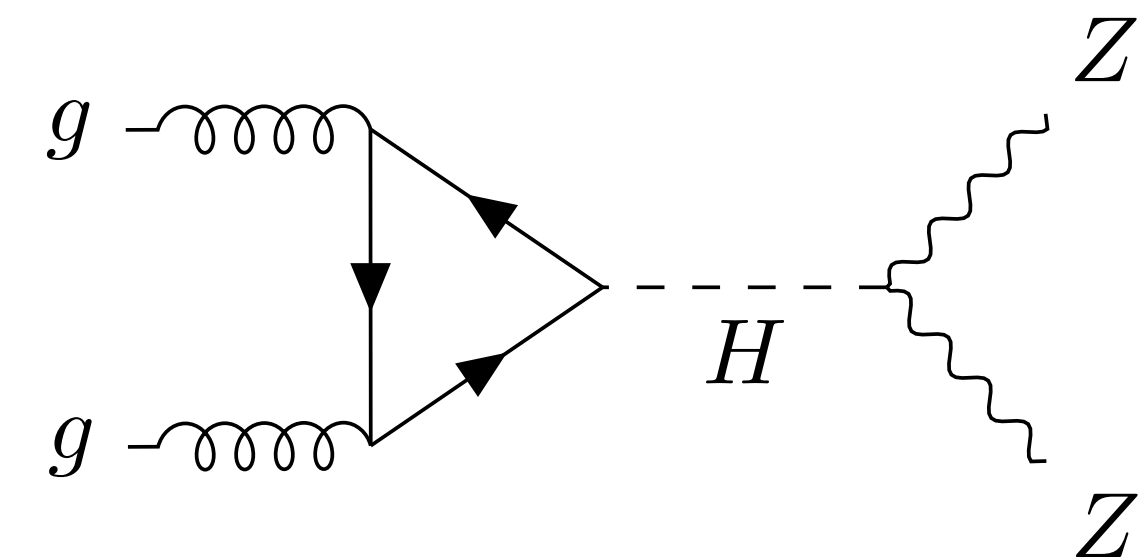
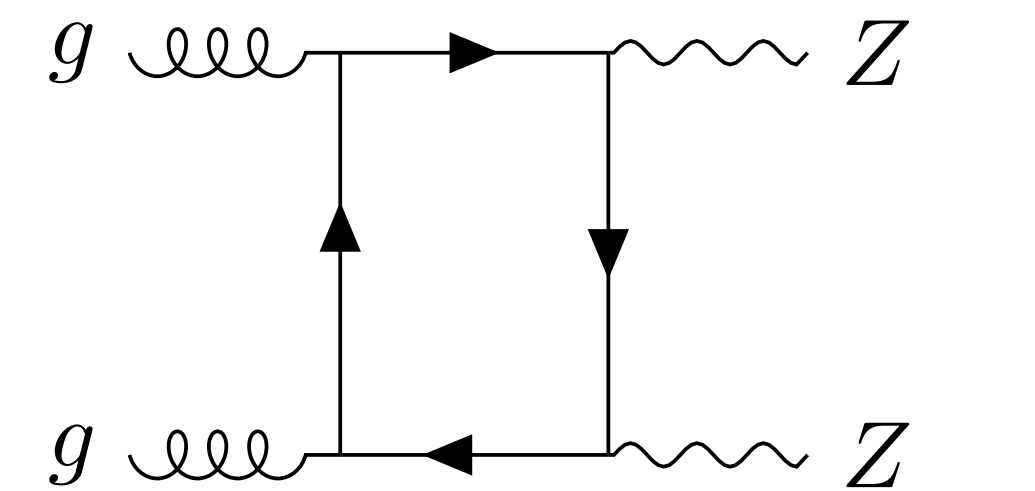
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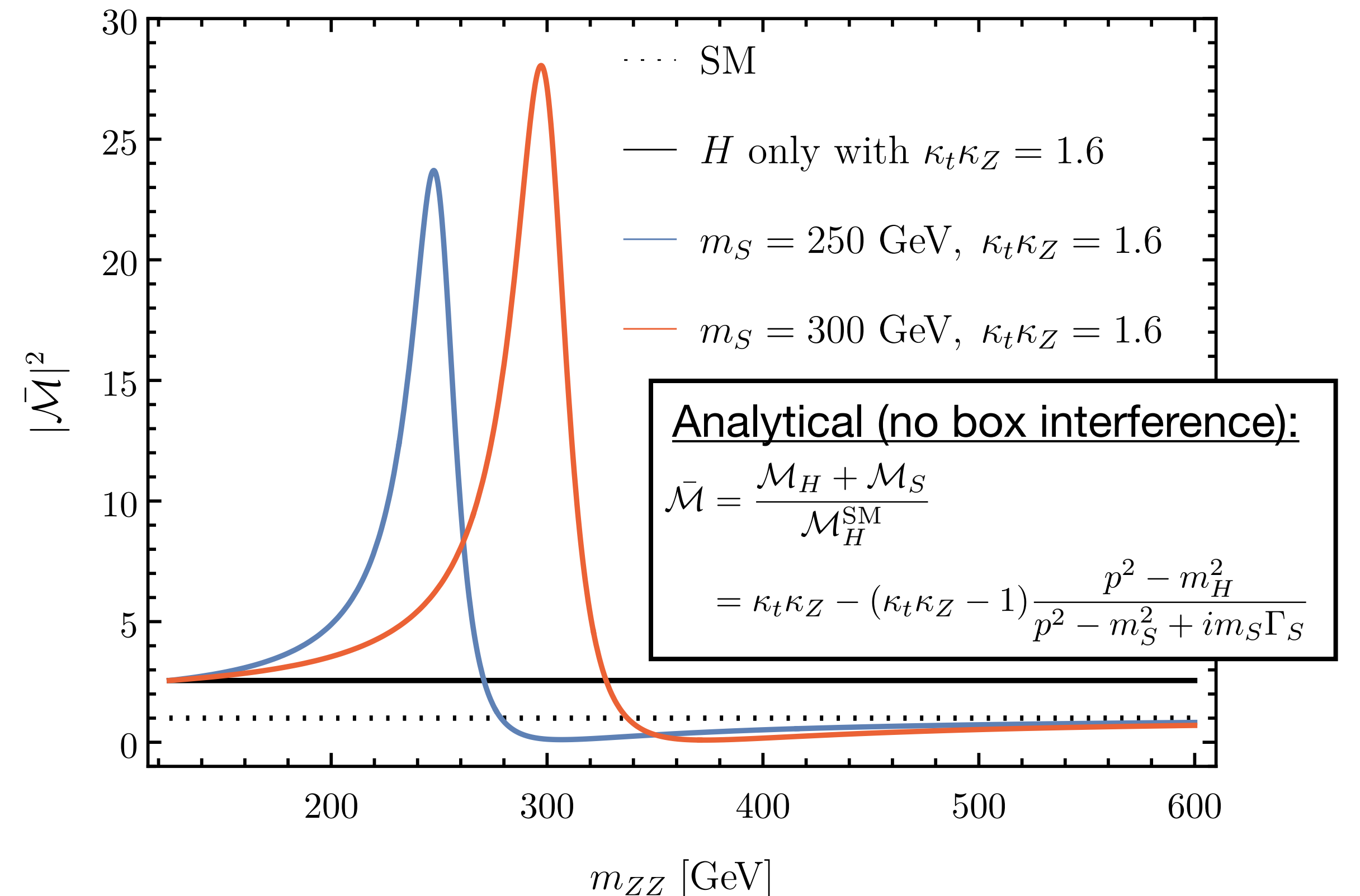
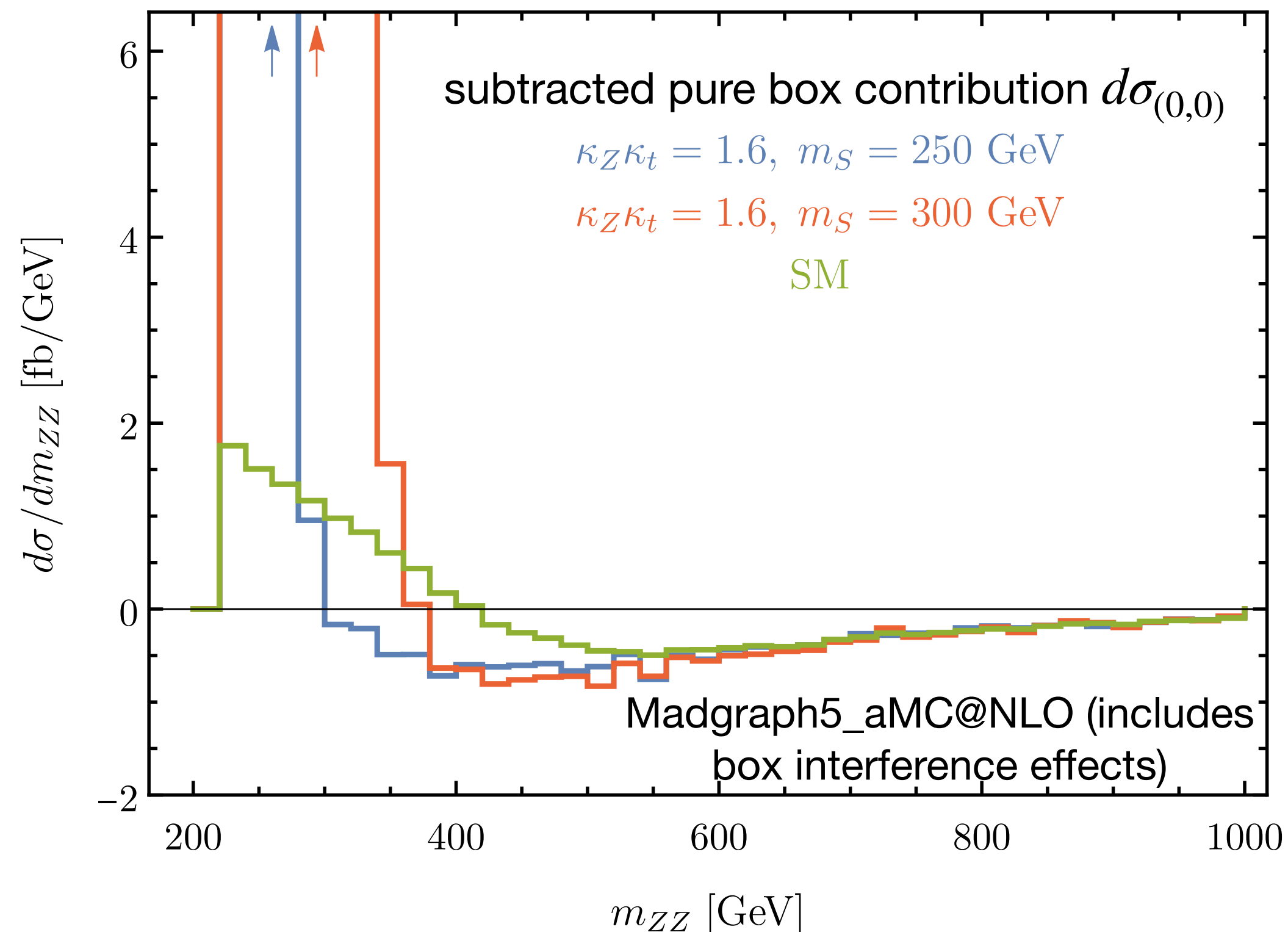
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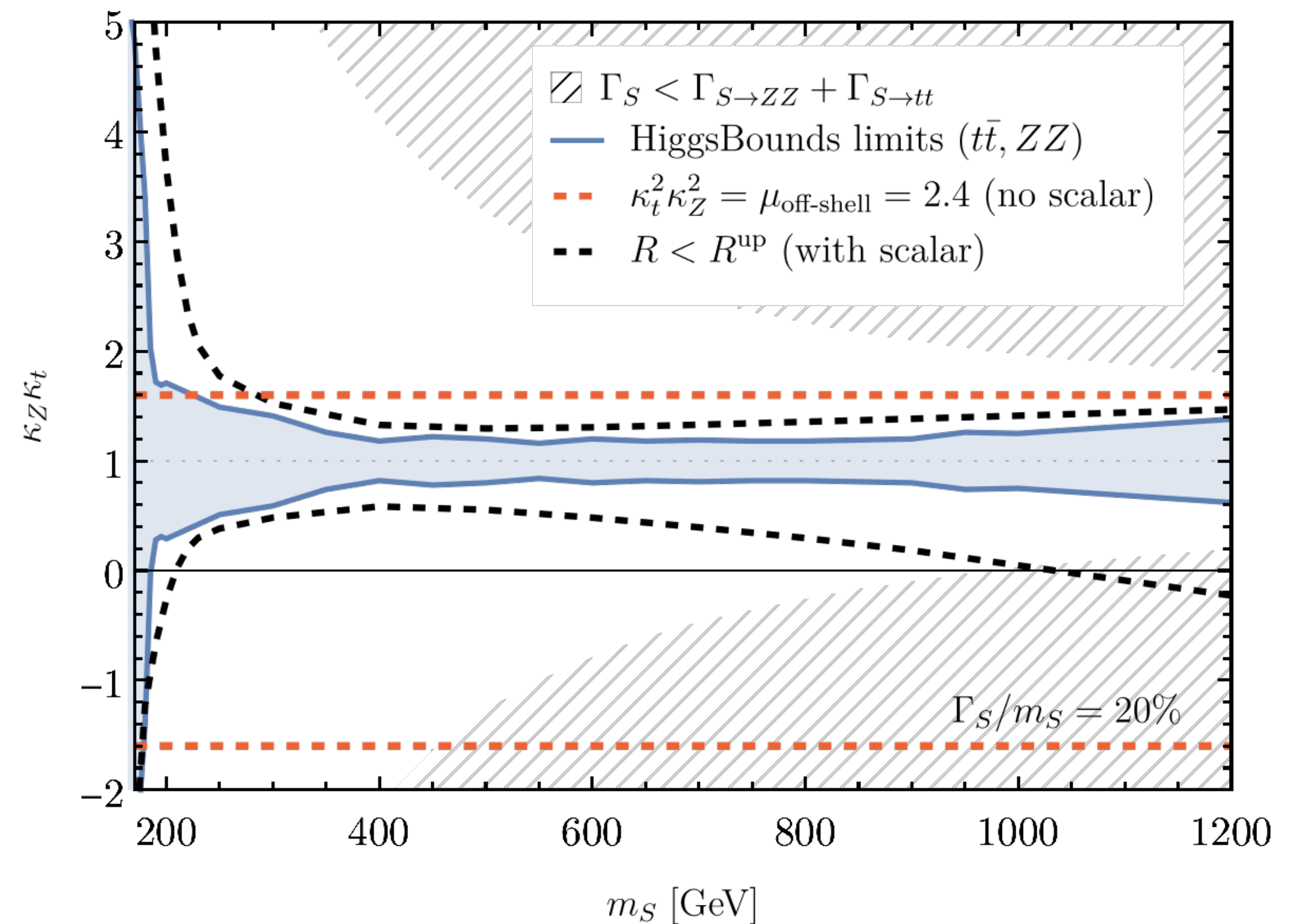
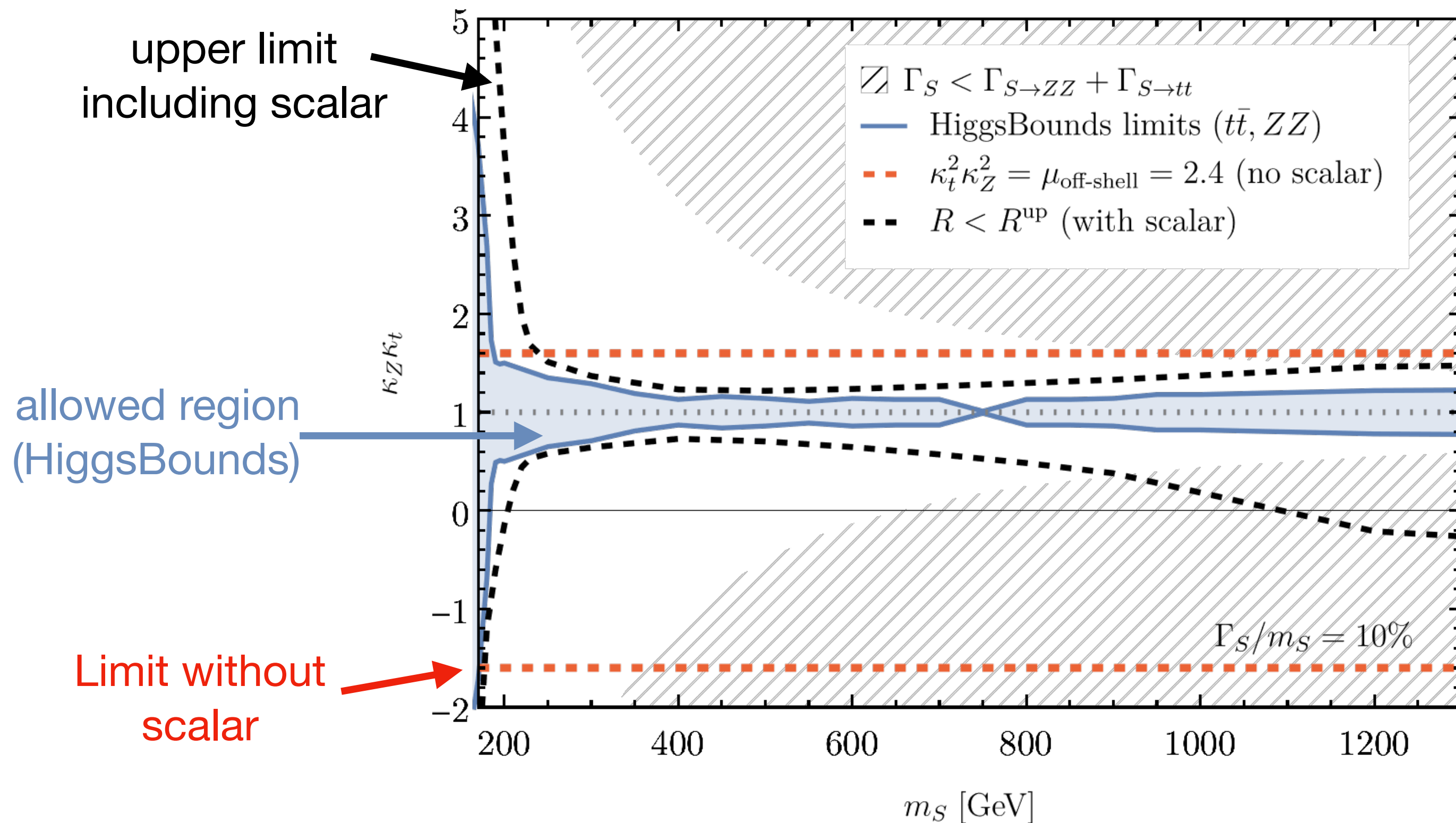
Propagating Scalar Singlet in the ZZ channel

- $C_{SZZ}C_{Stt}$ is replaced by $\kappa_Z\kappa_t$ using the sum rule
- Destructive interference could decrease the off-shell rate depending on m_S , κ_t , κ_Z [Logan '14]
- Simulations at $gg \rightarrow ZZ$ level with $m_{ZZ} > 220$ GeV
- Size and location of resonance is important



Impact of propagating scalar on Higgs width

- To check compatibility with $\mu_{\text{off}} < 2.4$, define the ratio:
$$R(\kappa_t \kappa_Z, C_{Stt} C_{SZZ}) = \frac{\sigma_{gg \rightarrow ZZ}(\kappa_t \kappa_Z, C_{Stt} C_{SZZ})}{\sigma_{gg \rightarrow ZZ}^{\text{SM}}}$$
- Upper limit on R from ATLAS off-shell signal strength:
$$R^{\text{up}} = \frac{\sigma_{(0,0)} + \sqrt{\mu_{\text{off}}^{\text{up}}} \sigma_{(2,0)} + \mu_{\text{off}}^{\text{up}} \sigma_{(4,0)}}{\sigma_{(0,0)} + \sigma_{(2,0)} + \sigma_{(4,0)}} = 3.4$$
- Compare with limits from **HiggsBounds*** assuming only decays to top-quarks and Z bosons
*modified to include [CMS-PAS-HIG-24-002]



Impact of propagating scalar on Higgs width

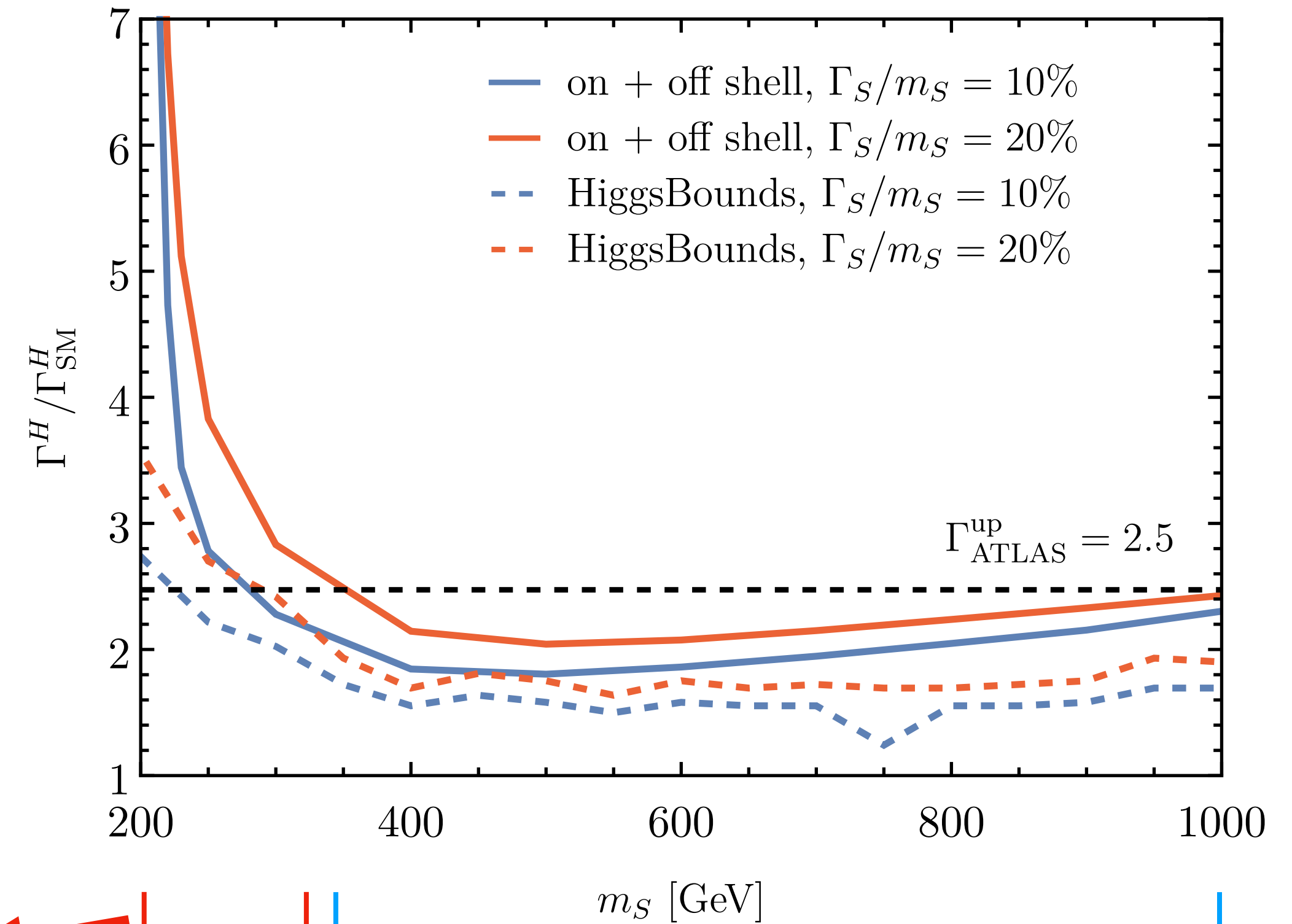
- Assuming no impact on on-shell signal strength from S , we can use:

$$\mu_{\text{on}} = \frac{\kappa_t^2 \kappa_Z^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

- Experimental bounds on on-shell signal strength:

$$\mu_{\text{on}}^{\text{ATLAS}} = 1.01_{-0.20}^{+0.23}$$

- Re-interpreted upper bound on $\kappa_t \kappa_Z$ as upper bound on Higgs width using on-shell results



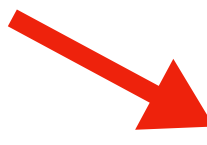
- For low masses the resonance is outside the off-shell region and interference decreases the rate $\rightarrow$ weaker bound on Γ_H
- HiggsBounds limits require $\Gamma^H / \Gamma_{\text{SM}}^H \lesssim 4$ (but are model-dependent)

For heavy scalars the presence of a resonance increases the off-shell rate and results on a stronger bound on Γ_H

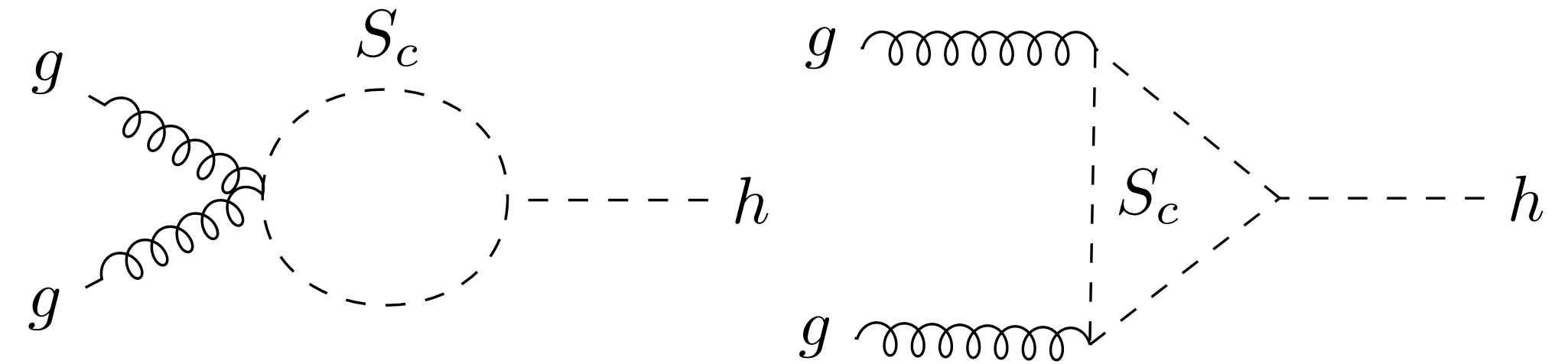
Gluon fusion modification: coloured scalar

- Investigate simple extension with coloured scalar S_c :

$$\mathcal{L} \supset D_\mu S_c D^\mu \bar{S}_c - m_{S_c}^2 S_c \bar{S}_c + \lambda_{S_c} \Phi^\dagger \Phi S_c^\dagger S_c$$

 leads to gluon-fusion modification

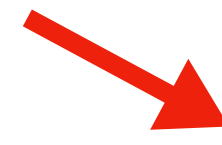
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- Similar parameterisation for the cross section $gg \rightarrow ZZ$



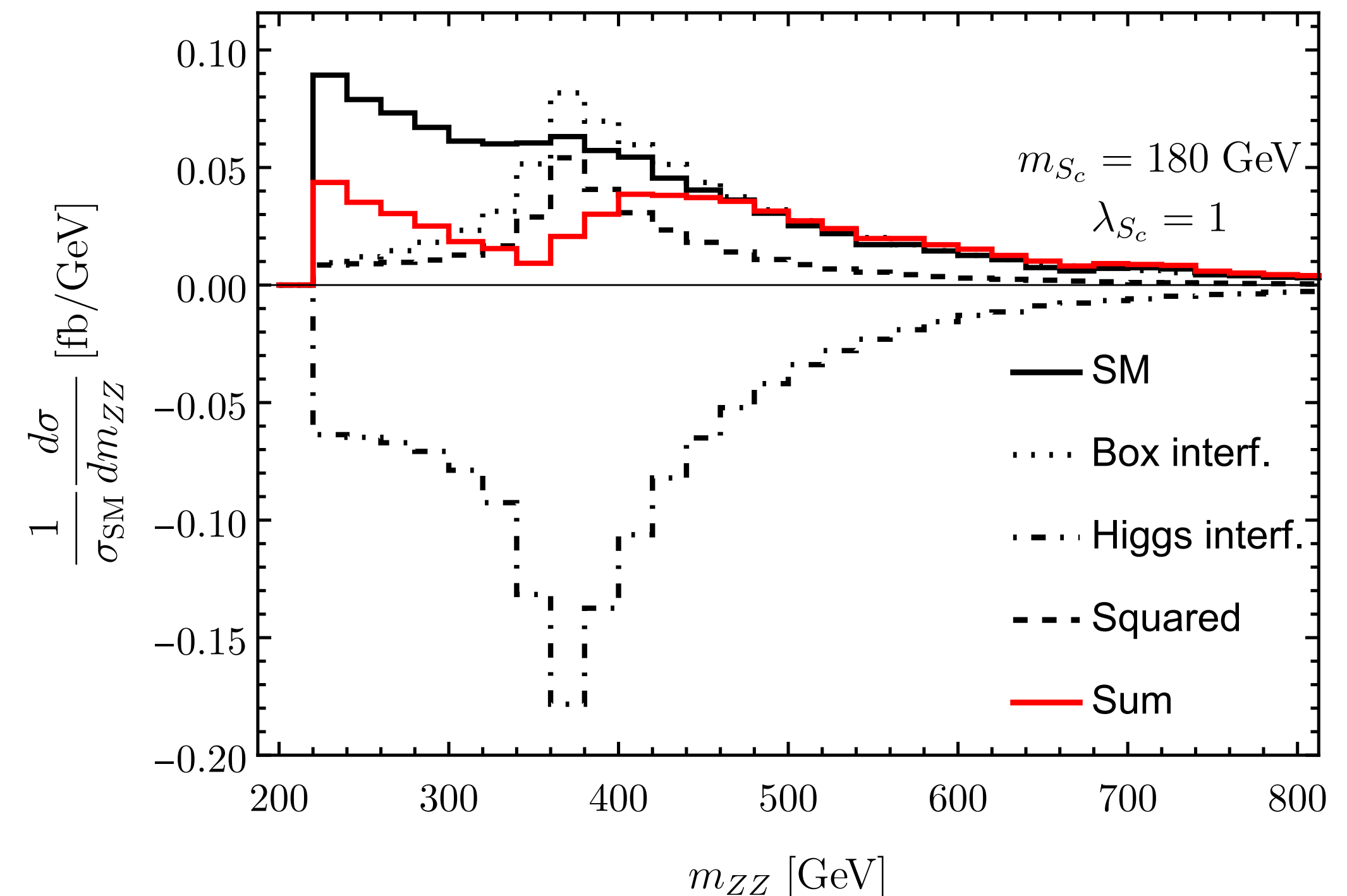
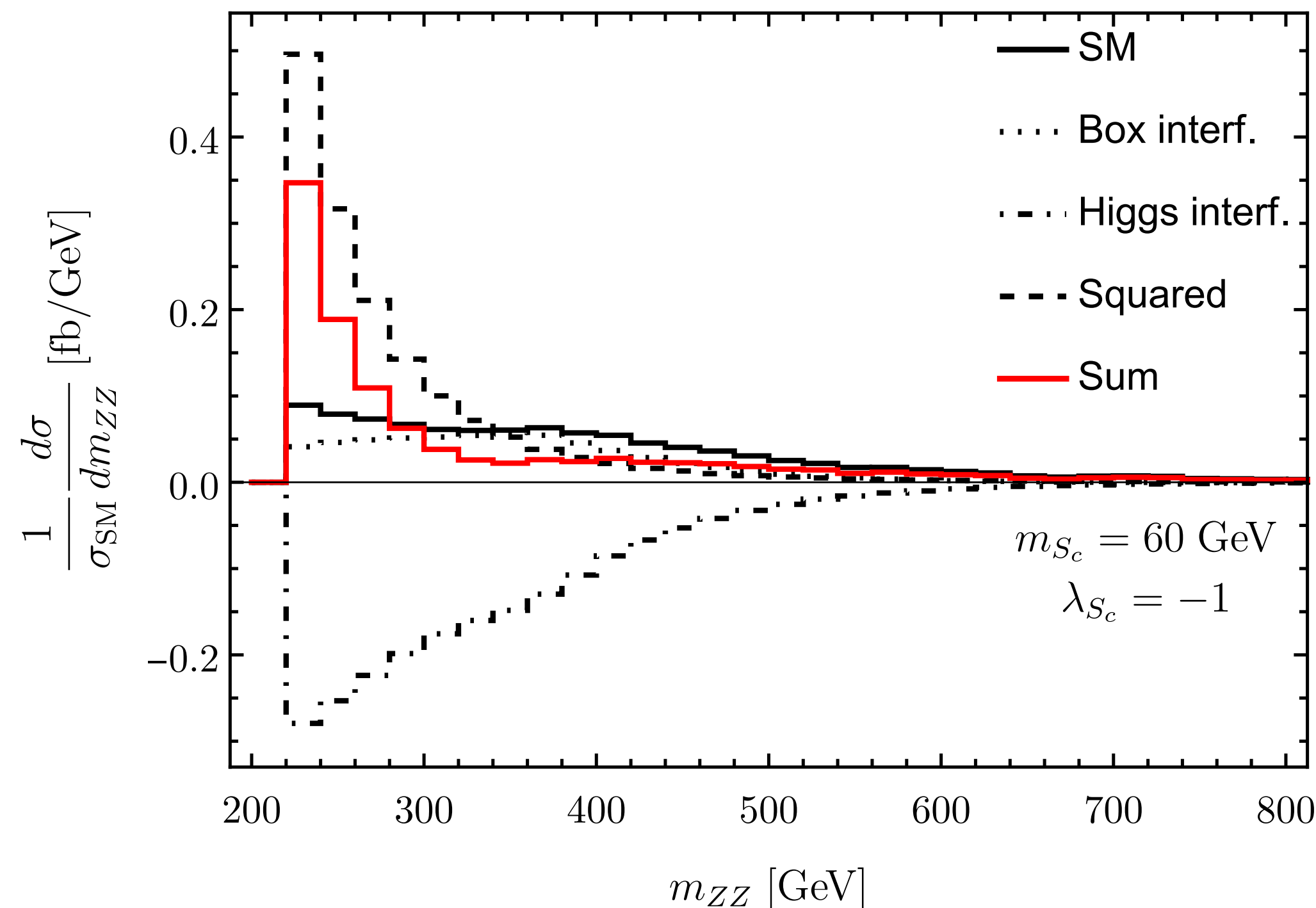
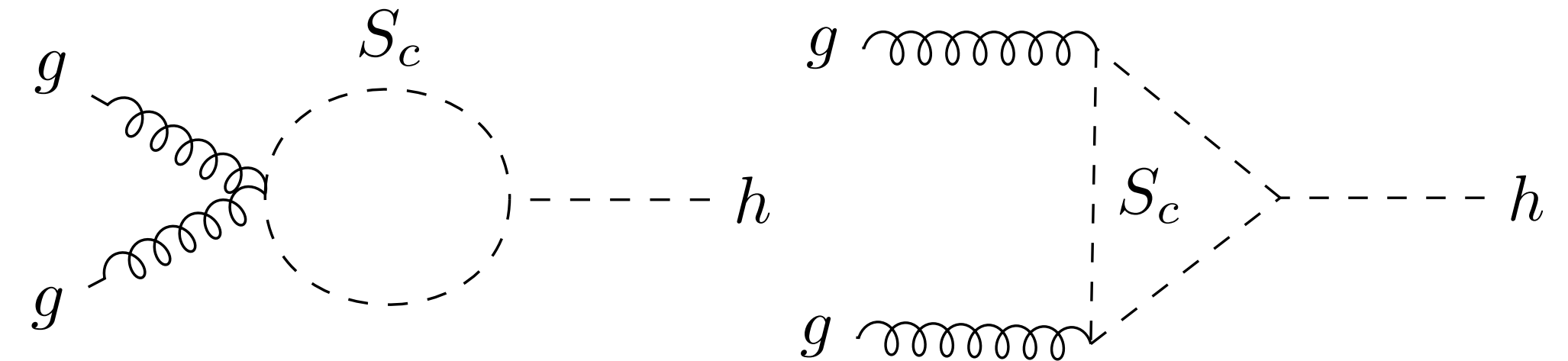
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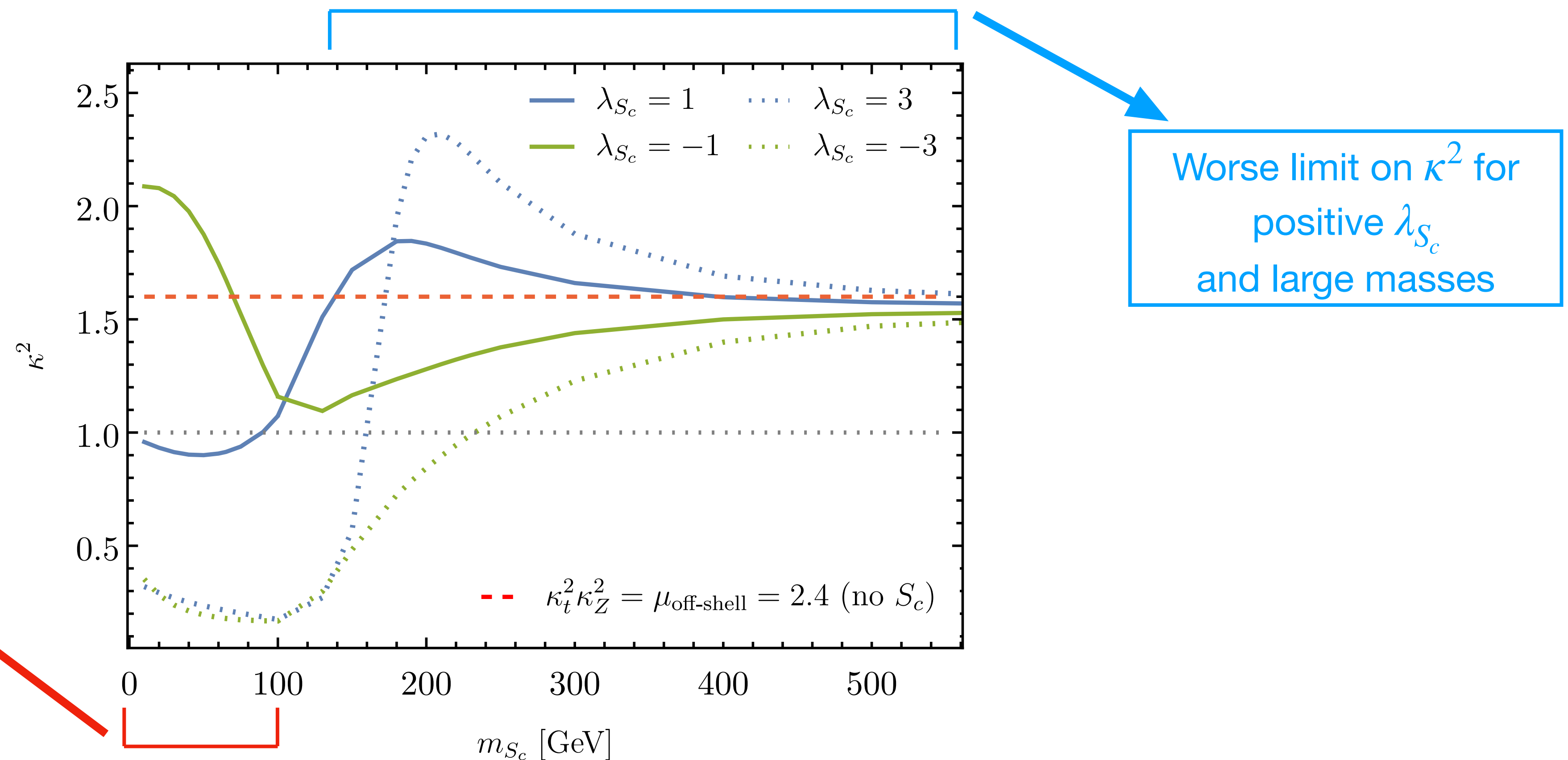
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Impact of propagating scalar on Higgs width

- Define ratio similar to previous case: $R(\kappa_t, \kappa_Z, \lambda_{S_c}) = \frac{\sigma_{gg \rightarrow ZZ}(\kappa_t, \kappa_Z, \lambda_{S_c})}{\sigma_{gg \rightarrow ZZ}^{\text{SM}}}$
- Upper limits** on $\kappa_t = \kappa_Z = \kappa$ from $R(\kappa, \kappa, \lambda_{S_c}) < R^{\text{up}}$

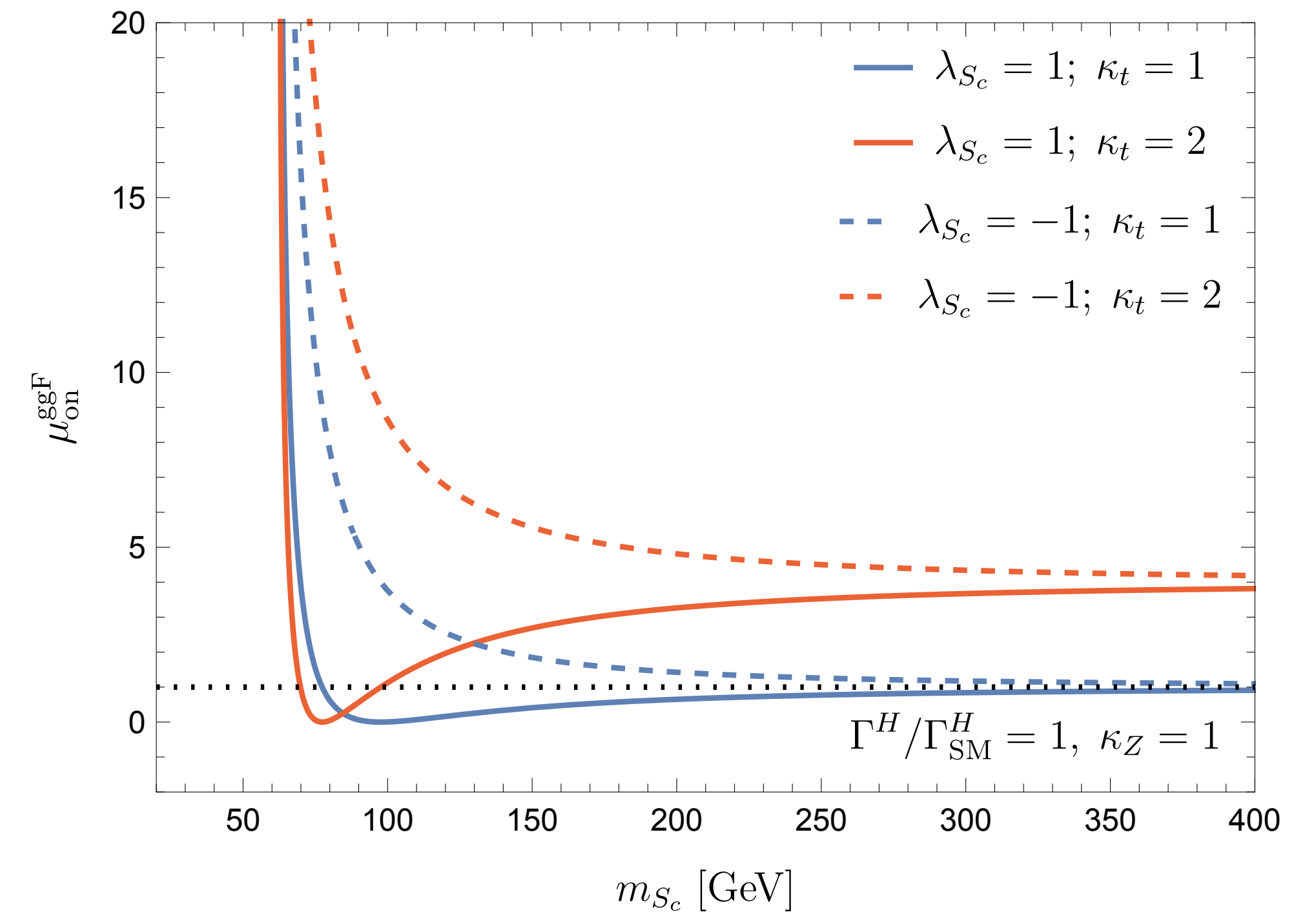
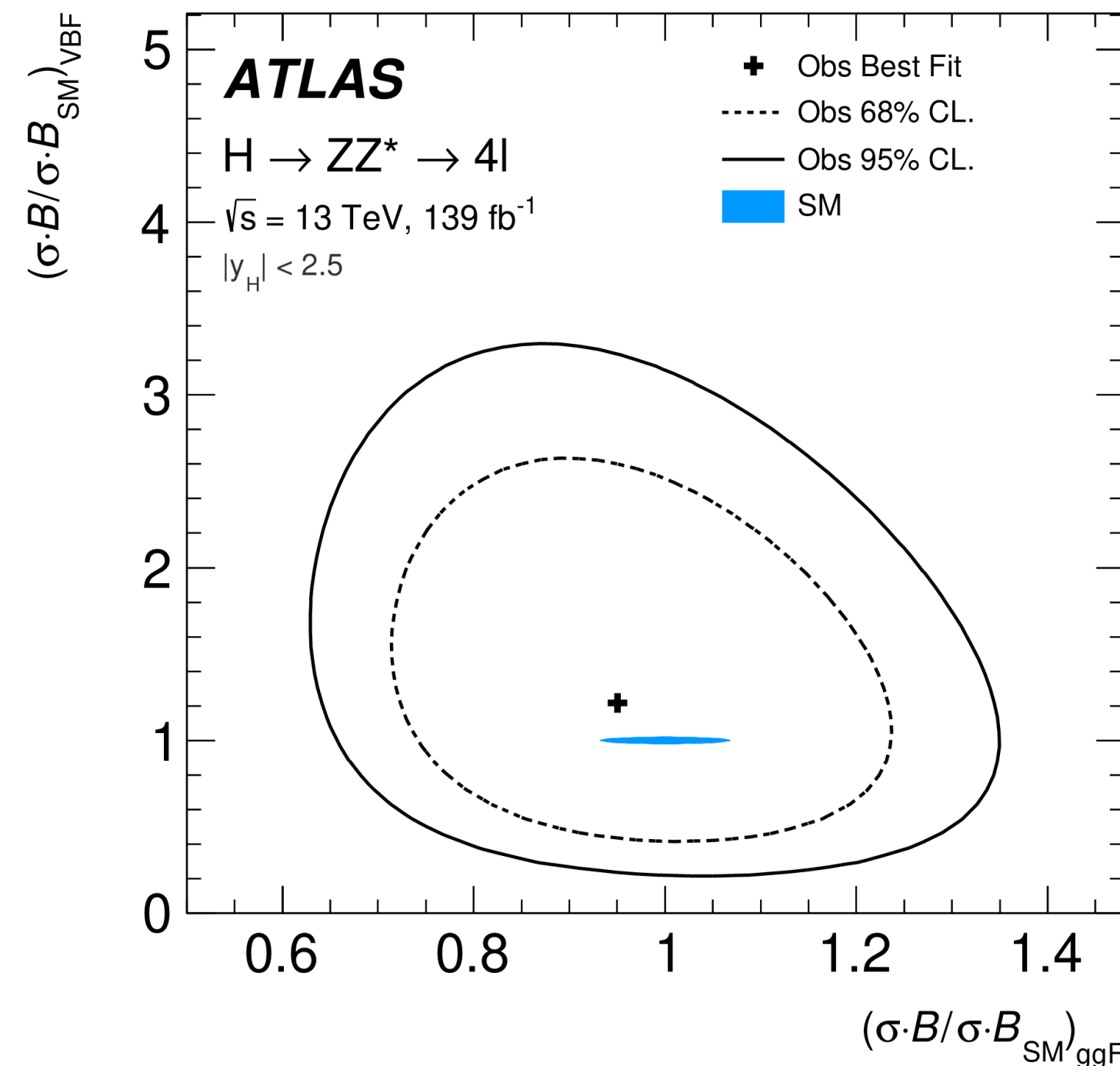


Coloured Scalar: on-shell

- Connecting to Higgs width more complicated:

$$\mu_{\text{on}}^{\text{ggF}} = \frac{\kappa_V^2}{\Gamma^H/\Gamma_{\text{SM}}^H} \left| \kappa_t + \frac{\lambda_{S_c} v^2 [1 + \tau_{S_c} f(\tau_{S_c})]}{m_H^2 [1 + (\tau_t - 1) f(\tau_t)]} \right|^2$$

$$f(\tau_i) = \begin{cases} \arcsin^2 \tau_i^{-1/2} & \tau_i > 1 \\ -\frac{1}{4} \left[\log \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi \right]^2 & \tau_i < 1 \end{cases} \quad \text{for } \tau_i = 4m_i^2/m_H^2$$

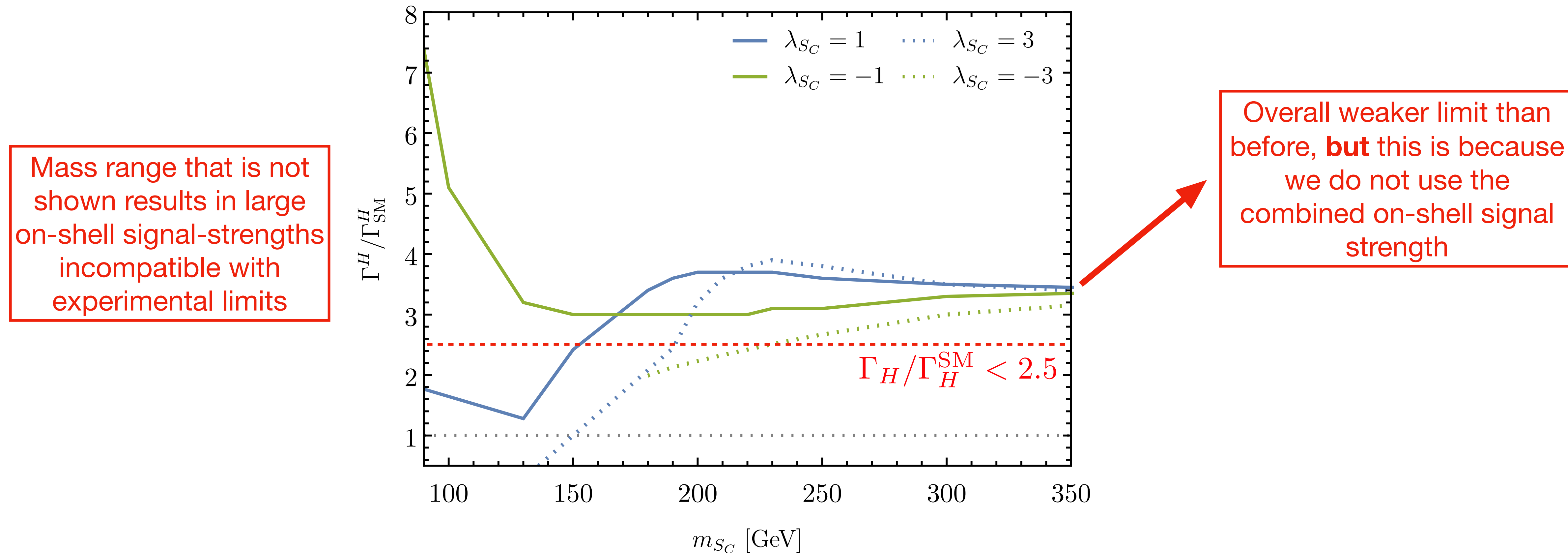


- VBF on-shell signal strength: $\mu_{\text{on}}^{\text{VBF}} = \frac{\kappa_V^4}{\Gamma_H/\Gamma_H^{\text{SM}}}$
- We use our allowed range of κ^2 and require that the on-shell signal strengths lie within the ATLAS 95 % CL bounds

[ATLAS 2004.03447]

Coloured Scalar: impact on Higgs width

- We obtain the upper bound on the total Higgs width compatible with both on-shell and off-shell results

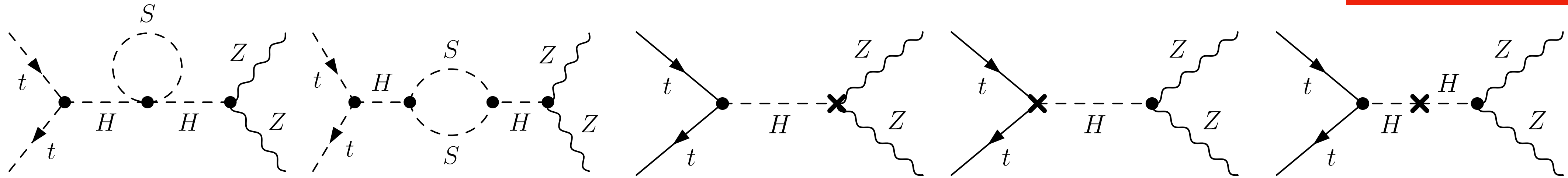


- Decays of the coloured scalar triplet to fermions require non-zero hypercharge and can not decay to gluons
 - The coloured scalar triplet could hadronise with a fractional electric charge
 $\implies$ **bounds are around 1 TeV** [CMS 1609.08382]

Loop modification of Higgs propagator: Higgs portal

- Scalar singlet modifying the Higgs propagator at 1-loop through Higgs portal coupling:

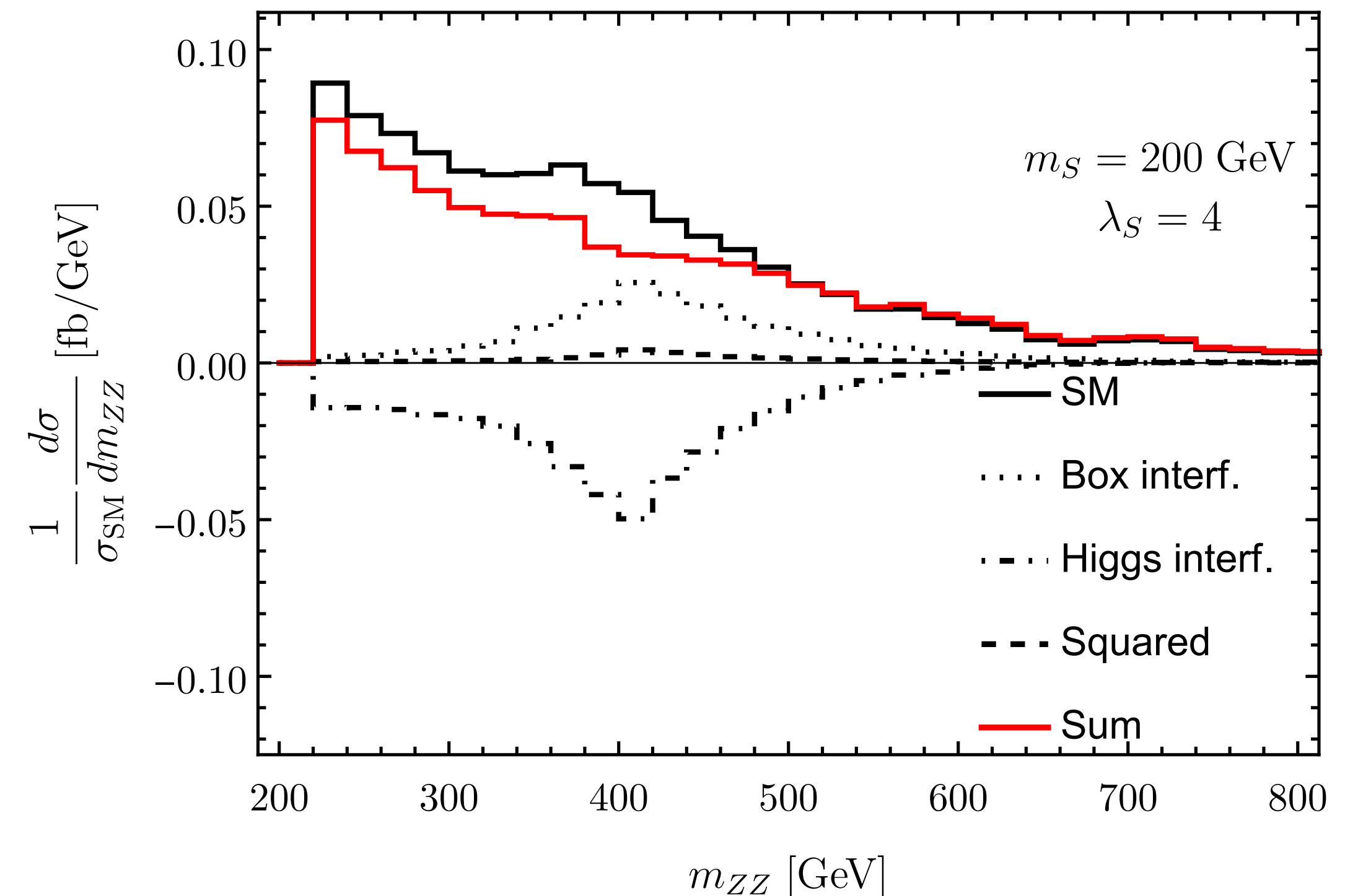
$$\mathcal{L} \supset -\lambda_S S^2 \Phi^\dagger \Phi$$



- Higgs amplitude $gg \rightarrow H \rightarrow ZZ$ modification factor:

$$\bar{\mathcal{M}} = \frac{\mathcal{M}_H + \mathcal{M}_S}{\mathcal{M}_H^{\text{SM}}} = 1 + \frac{\lambda_S^2 v^2}{8\pi^2(p^2 - m_H^2)} \times [B_0(p_H^2, m_S^2, m_S^2) - \text{Re}B_0(m_H^2, m_S^2, m_S^2)]$$

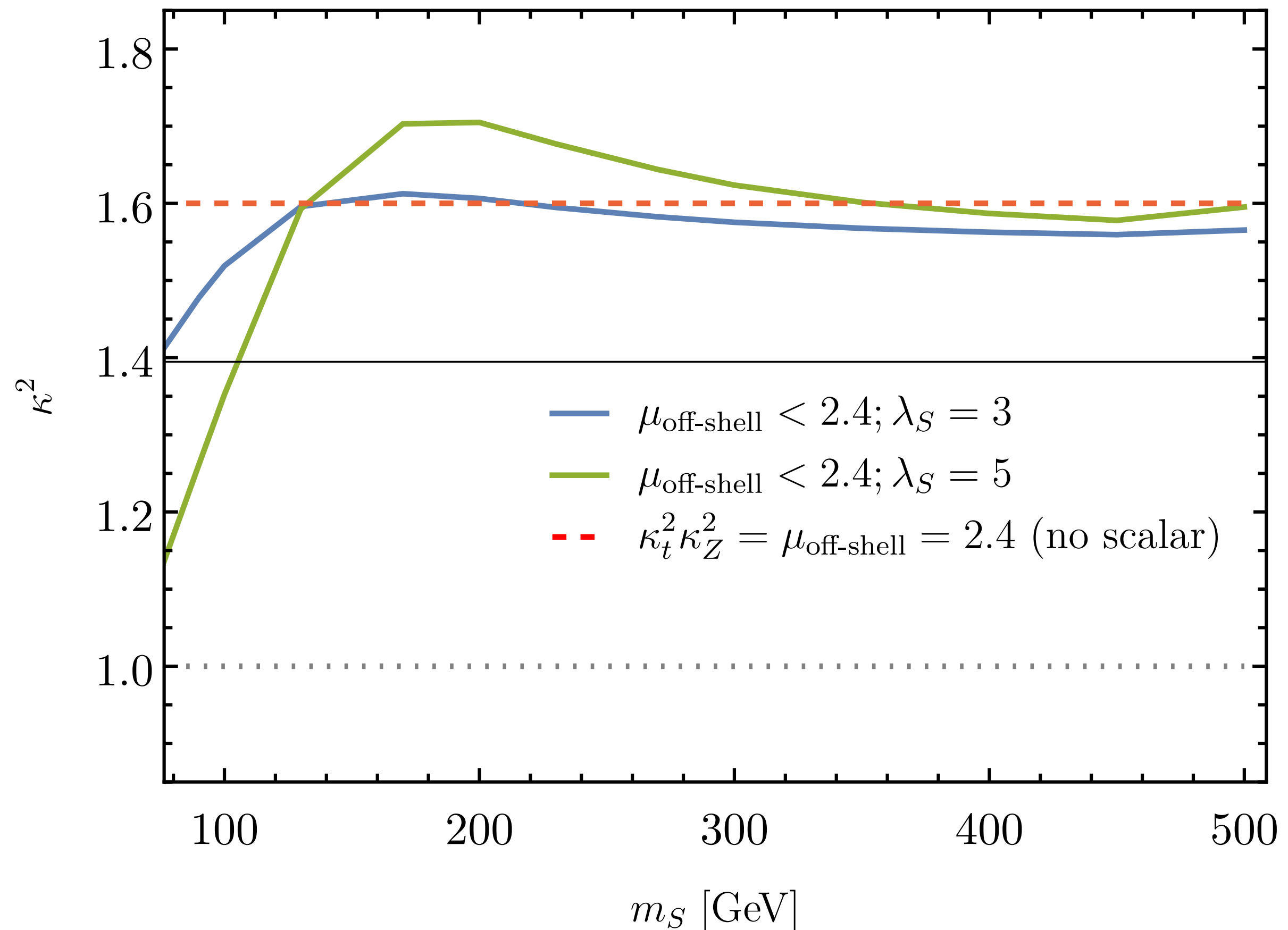
- Introduced in UFO model as form-factor in order to calculate $gg \rightarrow ZZ$ process with Higgs/box interference
- Similar cross section parameterisation as before



Impact of propagating scalar on Higgs width

- Upper limits similar to previous cases: $R(\kappa, \kappa, \lambda_S) = \frac{\sigma_{gg \rightarrow ZZ}(\kappa, \kappa, \lambda_S)}{\sigma_{gg \rightarrow ZZ}^{\text{SM}}} < R^{\text{up}}$
- Much smaller impact on κ^2 even at relatively large couplings λ_S

We could again use the on-shell signal strength to obtain a limit on Γ_H
→ However, given the small impact on κ^2 , we would not get a large impact on Γ_H



Conclusions

- A direct determination of the Higgs width is not possible in the near future
→ need to rely on **indirect bounds** from the off-shell ZZ channel
 - Effects in the off-shell $gg \rightarrow ZZ$ channel that **decrease** the total rate, could allow for enhanced Higgs couplings and thus a larger Higgs width Γ_H
 - We assessed the impact on the Higgs width from three simplified scenarios:
 - ➡ An additional propagating scalar $gg \rightarrow S \rightarrow ZZ$
 - ➡ Modification of the Higgs gluon-fusion $gg \rightarrow H$ due to a coloured scalar
 - ➡ Modification the Higgs propagator with a scalar loop contribution
- Reduction of off-shell rate from interference effects
- Overall, the indirect Higgs width limit remains robust, except for effects arising from scalars with relatively low masses → **however** searches for such scalars can widen the validity of the Higgs width limit

Conclusions

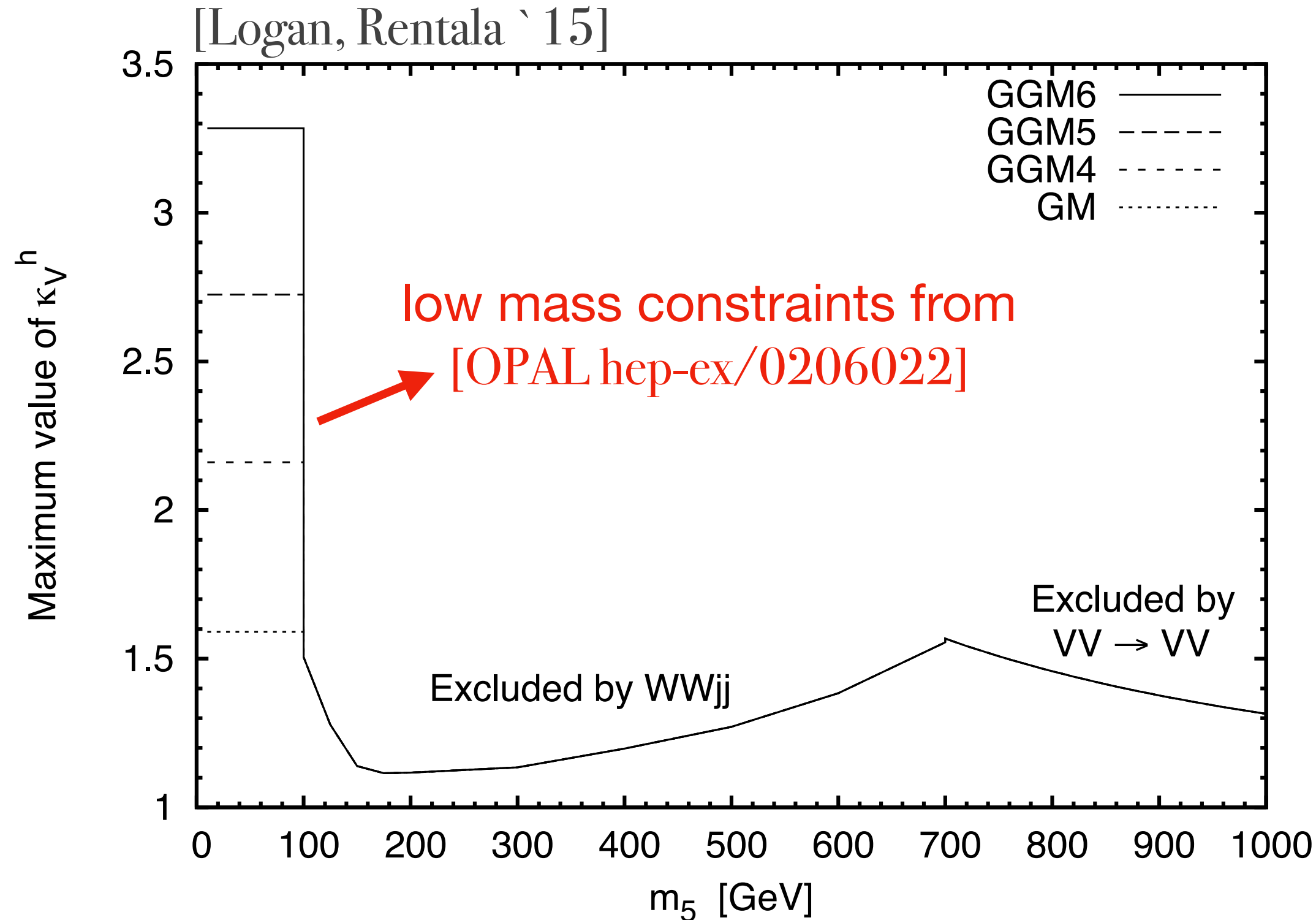
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Thank you!

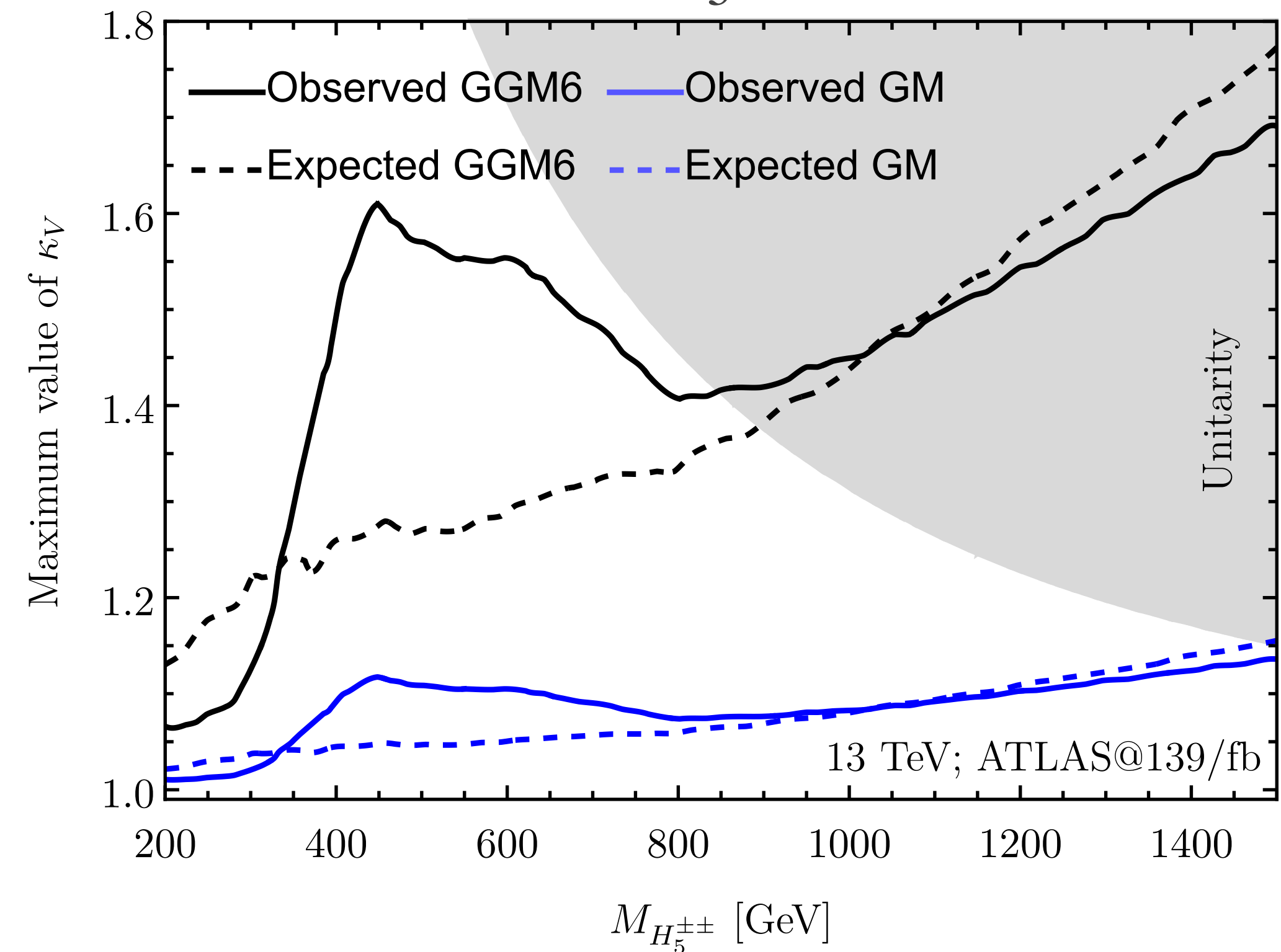
Backup

Enhancing κ_V

- Increasing κ_V quickly leads to issues with perturbative unitarity in many models
- Allowed in Georgi-Machacek models



limits obtained using results of [ATLAS 2312.00420]
(VBF production of $H_5^{\pm\pm}$ with decays to WW)



Gluon fusion modification: comparison

- Investigate simple extension with coloured scalar S_c :

$$\mathcal{L} \supset D_\mu S_c D^\mu \bar{S}_c - m_{S_c}^2 S_c \bar{S}_c + \lambda_{S_c} \Phi^\dagger \Phi S_c^\dagger S_c$$

 leads to gluon-fusion modification

- Perturbativity is more complicated than before, we do not enforce a sum-rule

Simple analytical setup:

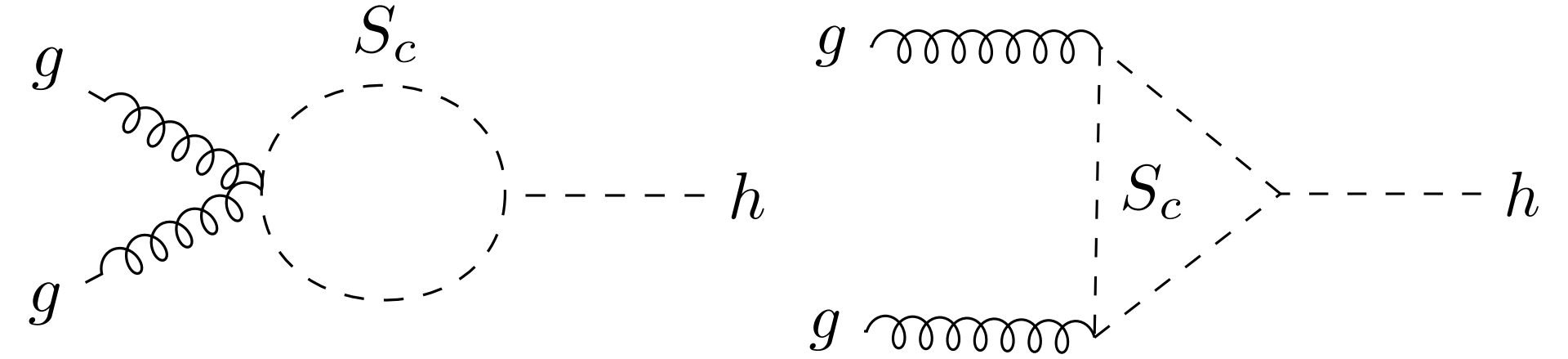
Modification of SM Higgs contribution:

$$\bar{\mathcal{M}} = \kappa_Z \left(\kappa_t + \frac{\lambda_{S_c} v^2 [1 + \tau_{S_c} f(\tau_{S_c})]}{m_H^2 [1 + (\tau_t - 1) f(\tau_t)]} \right)$$

$$\text{for } \tau_i = 4m_i^2/p_H^2$$

Loop function:

$$f(\tau_i) = \begin{cases} \arcsin^2 \tau_i^{-1/2} & \tau_i > 1 \\ -\frac{1}{4} \left[\log \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi \right]^2 & \tau_i < 1 \end{cases}$$



Numerical setup:

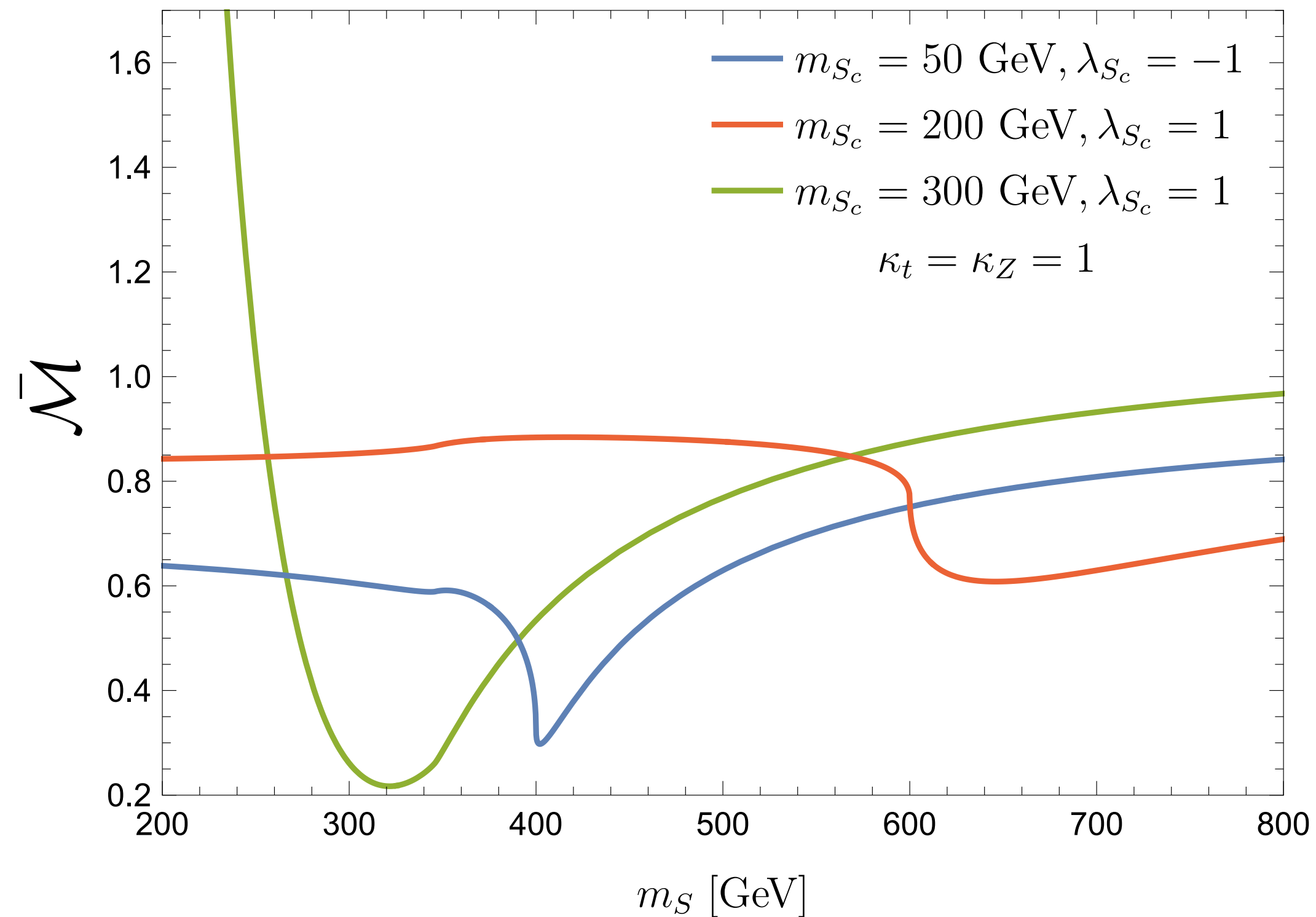
Parameterised cross section for $gg \rightarrow ZZ$:

$$\begin{aligned} d\sigma_{gg \rightarrow ZZ}(\kappa_t, \kappa_Z, \lambda_{S_c}) = & d\sigma_{(0,0)} + \kappa_t \kappa_Z d\sigma_{(2,0)} + \kappa_t^2 \kappa_Z^2 d\sigma_{(4,0)} \\ & + \kappa_Z \lambda_{S_c} d\sigma_{(1,1)} + \kappa_t \kappa_Z^2 \lambda_{S_c} d\sigma_{(3,1)} \\ & + \kappa_Z^2 \lambda_{S_c}^2 d\sigma_{(2,2)} \end{aligned}$$

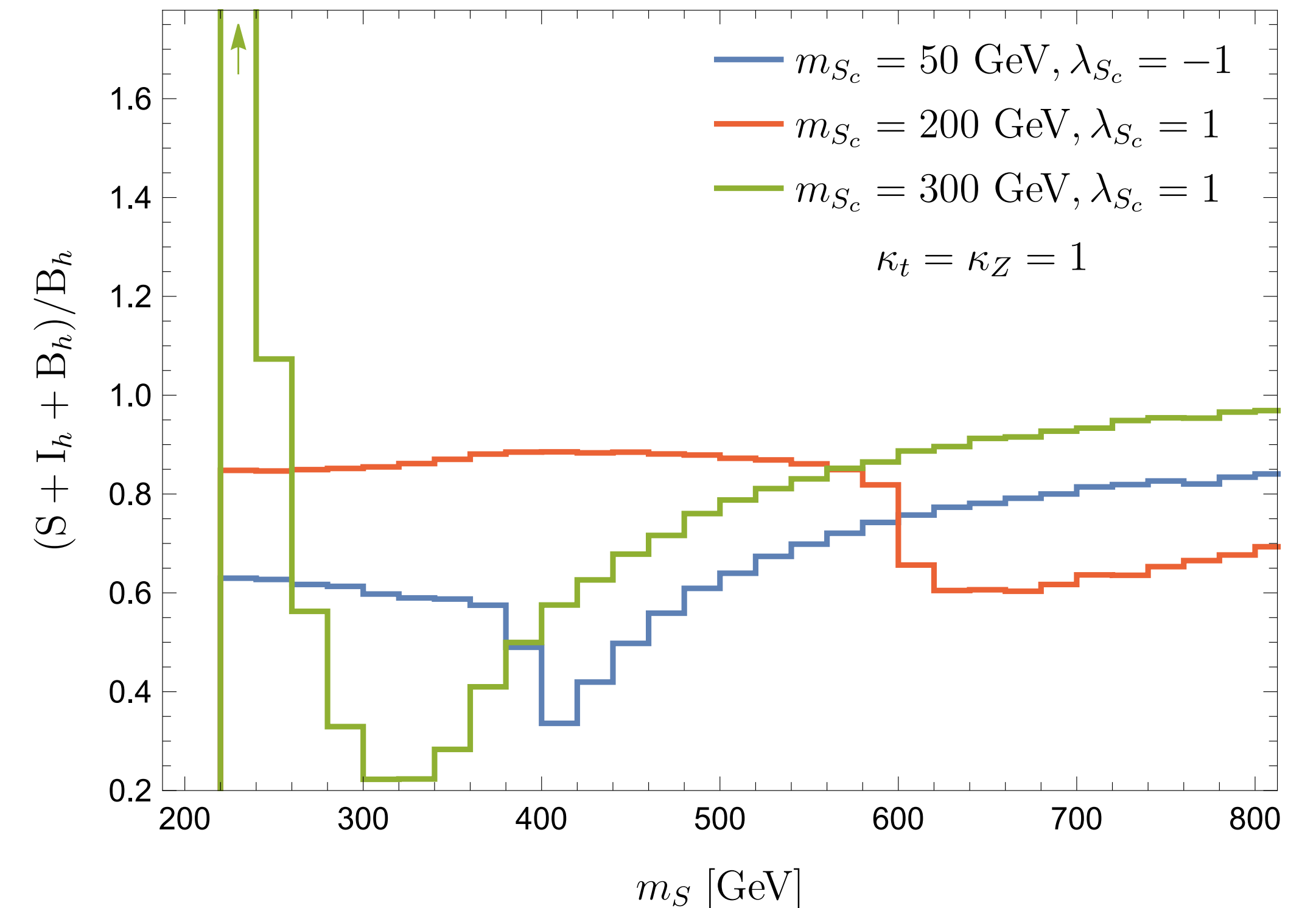
→ Can compare when box-contributions are not included (i.e. only $d\sigma_{(4,0)}$, $d\sigma_{(3,1)}$, $d\sigma_{(2,2)}$)

Coloured scalar: comparison with analytical

Simple analytical setup:



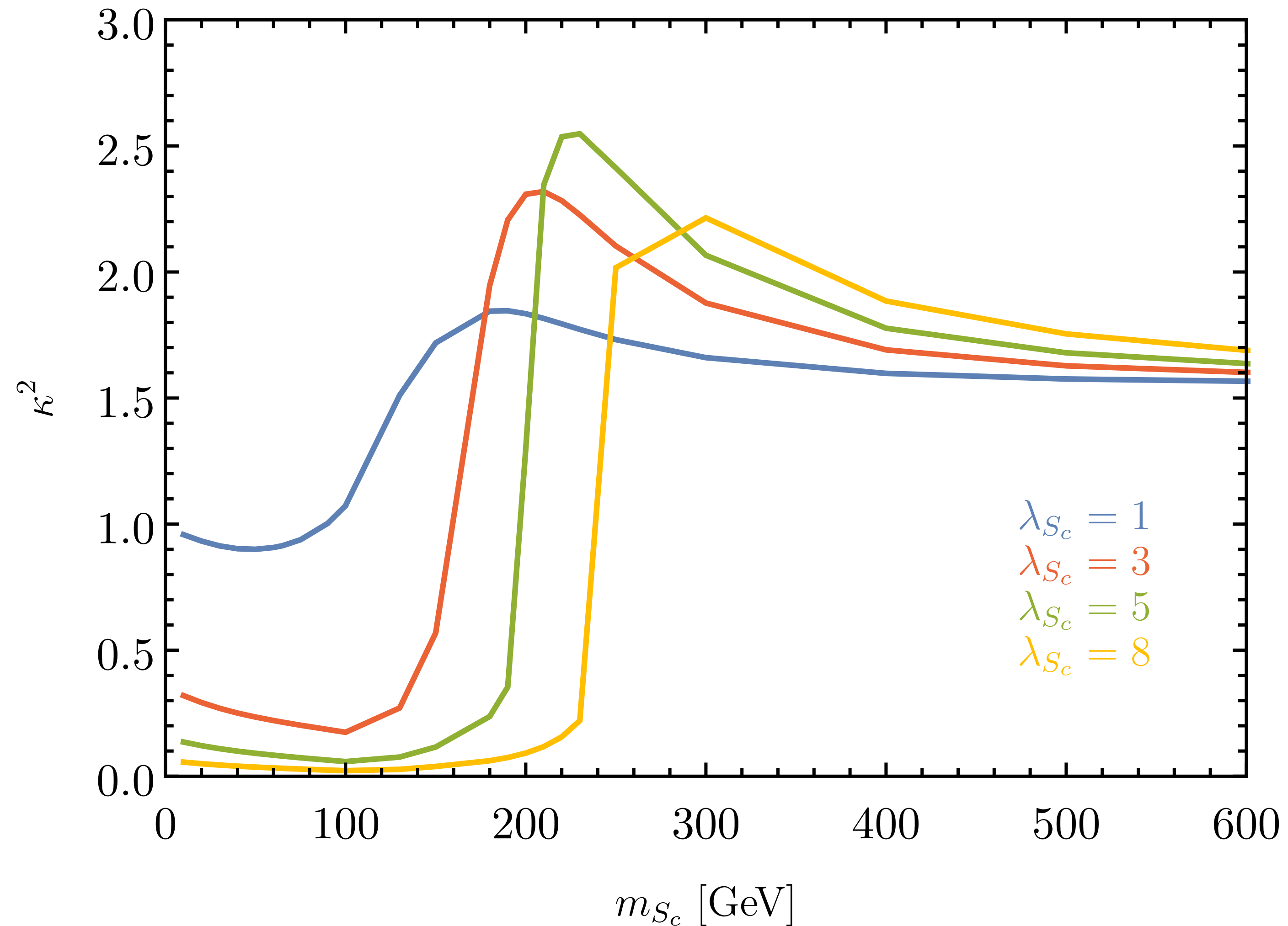
Numerical setup:



- For small masses negative λ_{S_c} induces negative interference (and vice-versa for large masses)

Coloured scalar κ^2 limits

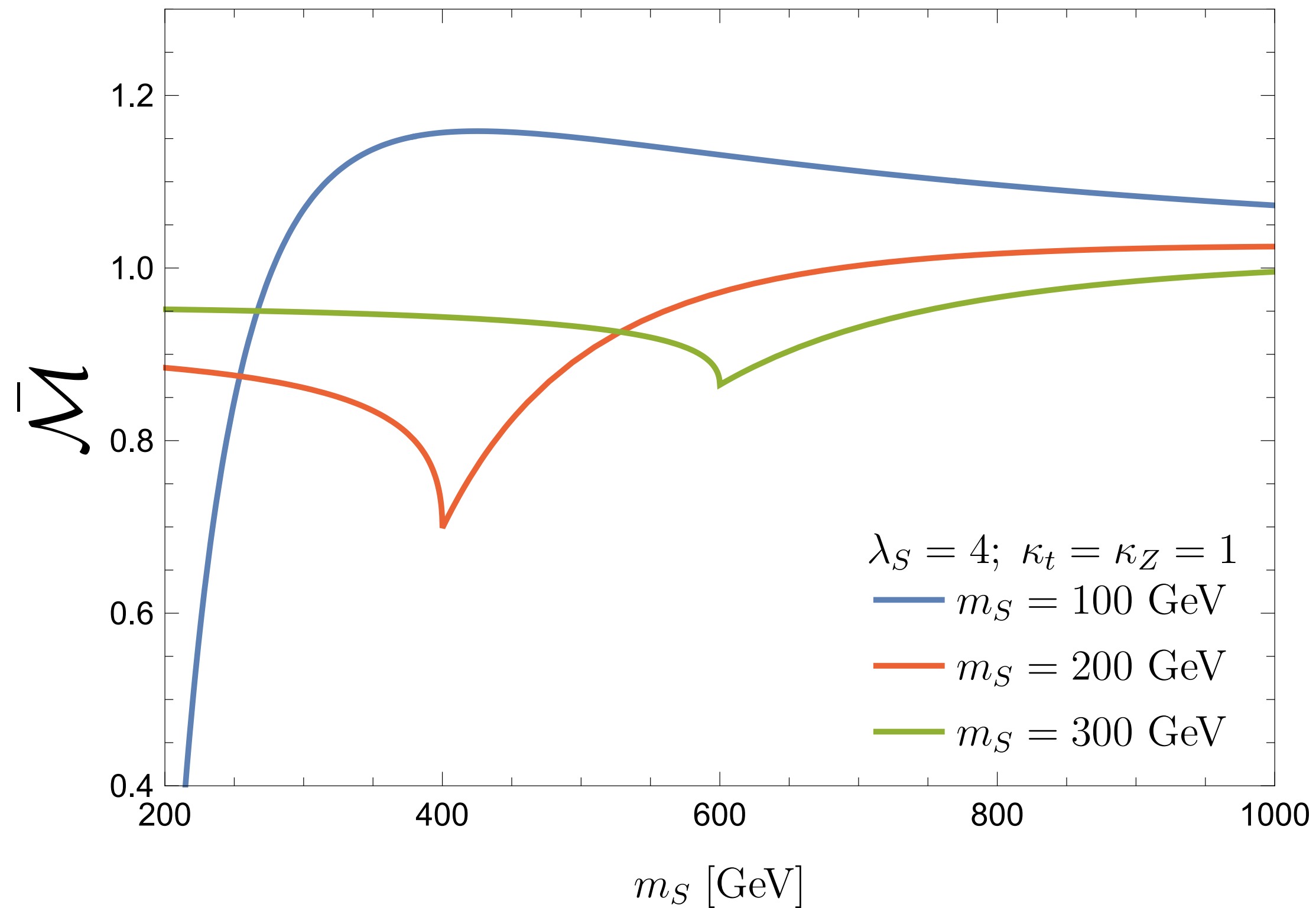
- Increasing λ_{S_c} does not necessarily increase upper limit on κ^2



Higgs portal: comparison with analytical

- Check implementation without any box contributions

Analytical setup:



Numerical setup:

