מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

MINERVA
STIFTUNG

Probing Higgs-Portal Dark Matter with Vector-Boson Fusion

Jan Heisig, Michael Krämer, E.M., Alexander Mück
JHEP **03** (2020), 183

Eric Madge

Weizmann Institute of Science

PANIC – September 5, 2021

Introduction

- search for Higgs portal DM in VBF
  - $m_{\text{DM}} < m_h/2 \longrightarrow$ invisible Higgs decays, e.g. CMS – 1809.05937, ATLAS – 1809.06682
  - $m_{\text{DM}} > m_h/2 \longrightarrow$ via off-shell Higgs, e.g. Ruhrdorfer et al. – 1910.04170

Introduction

- search for Higgs portal DM in VBF
  - $m_{\text{DM}} < m_h/2 \longrightarrow$ invisible Higgs decays, e.g. CMS – 1809.05937, ATLAS – 1809.06682
  - $m_{\text{DM}} > m_h/2 \longrightarrow$ via off-shell Higgs, e.g. Ruhrdorfer et al. – 1910.04170
- here: also consider resonance region $m_{\text{DM}} \simeq m_h/2$

  motivation: can satisfy relic density and direct detection constraints

  $\Longrightarrow$ need to include running width in Higgs propagator

Introduction

- search for Higgs portal DM in VBF
  - $m_{\text{DM}} < m_h/2 \longrightarrow$ invisible Higgs decays, e.g. CMS – 1809.05937, ATLAS – 1809.06682
  - $m_{\text{DM}} > m_h/2 \longrightarrow$ via off-shell Higgs, e.g. Ruhrdorfer et al. – 1910.04170
- here: also consider resonance region $m_{\text{DM}} \simeq m_h/2$

  motivation: can satisfy relic density and direct detection constraints

  $\Longrightarrow$ need to include running width in Higgs propagator
- Outline:
  - current LHC constraints: 13 TeV, 35.9 fb^{-1} $\longrightarrow$ reinterpretation of CMS search
  - limits for HL- (14 TeV, 3 ab^{-1}) and HE-LHC (27 TeV, 15 ab^{-1}), including systematics $\longrightarrow$ MC based on CMS projections

Scalar Singlet Higgs Portal Dark Matter

- SM + real singlet scalar $S + Z_2 \implies$ simple DM model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_{S,0}^2 S^2 - \frac{1}{2}\lambda_S S^4 - \frac{1}{2}\lambda_{\text{HP}} S^2 \Phi^\dagger \Phi$$

- If $m_S < \frac{m_h}{2}$: invisible Higgs decays

$$\Gamma_{\text{inv}} = \frac{\lambda_{\text{HP}}^2 v^2}{32\pi m_h} \sqrt{1 - 4\frac{m_S^2}{m_h^2}}$$

Scalar Singlet Higgs Portal Dark Matter

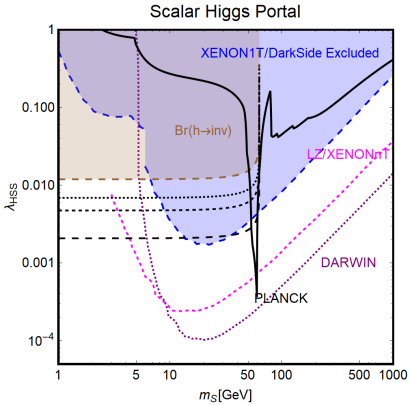
- SM + real singlet scalar S + Z_2 $\Longrightarrow$ simple DM model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_{S,0}^2 S^2 - \frac{1}{2}\lambda_S S^4 - \frac{1}{2}\lambda_{\text{HP}} S^2 \Phi^\dagger \Phi$$

- If $m_S < \frac{m_h}{2}$: invisible Higgs decays

$$\Gamma_{\text{inv}} = \frac{\lambda_{\text{HP}}^2 v^2}{32\pi m_h}\sqrt{1 - 4\frac{m_S^2}{m_h^2}}$$

- mass range favored by global fits / motivated by relic density and DM direct detection constraints:
  - high masses: $m_S \gtrsim 1\,\text{TeV}$ $\longrightarrow$ too heavy for DD



[Arcadi et al. – 1903.03616]

Scalar Singlet Higgs Portal Dark Matter

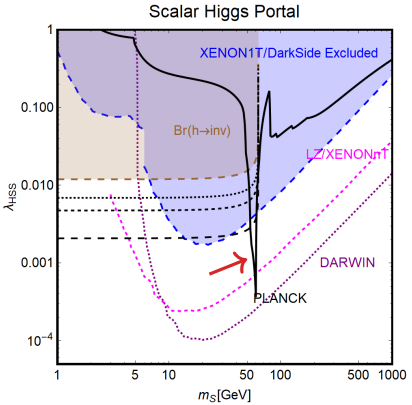
- SM + real singlet scalar S + Z_2 $\Longrightarrow$ simple DM model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_{S,0}^2 S^2 - \frac{1}{2}\lambda_S S^4 - \frac{1}{2}\lambda_{\text{HP}} S^2 \Phi^\dagger \Phi$$

- If $m_S < \frac{m_h}{2}$: invisible Higgs decays

$$\Gamma_{\text{inv}} = \frac{\lambda_{\text{HP}}^2 v^2}{32\pi m_h}\sqrt{1 - 4\frac{m_S^2}{m_h^2}}$$

- mass range favored by global fits / motivated by relic density and DM direct detection constraints:
  - high masses: $m_S \gtrsim 1\,\text{TeV}$ $\longrightarrow$ too heavy for DD
  - close to h resonance: $m_S \simeq \frac{m_h}{2}$ $\longrightarrow$ small λ_{HP}



[Arcadi et al. – 1903.03616]

LHC Limits at 13 TeV

- based on CMS – 1809.05937
- search for invisible h decays in VBF: $pp \to h + jj\,,\ h \to \text{inv}$
- $\sqrt{s} = 13\,\text{TeV},\ \mathcal{L} = 35.9\,\text{fb}^{-1}$

LHC Limits at 13 TeV

- based on CMS – 1809.05937
- search for invisible h decays in VBF: $pp \to h + jj\,,\ h \to \text{inv}$
- $\sqrt{s} = 13\,\text{TeV},\ \mathcal{L} = 35.9\,\text{fb}^{-1}$
- cuts:

$$p_T^{j_1} > 80\,\text{GeV}, \qquad p_T^{j_2} > 40\,\text{GeV}, \qquad |\eta_j| < 4.7,$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0, \qquad |\Delta\eta_{jj}| > 4.0, \qquad |\Delta\phi_{jj}| < 1.5,$$
$$M_{jj} > 1.3\,\text{TeV}, \qquad \not{E}_T > 250\,\text{GeV}, \qquad \ldots$$

LHC Limits at 13 TeV

- based on CMS – 1809.05937
- search for invisible h decays in VBF: $pp \to h + jj\,,\ h \to \text{inv}$
- $\sqrt{s} = 13\,\text{TeV},\ \mathcal{L} = 35.9\,\text{fb}^{-1}$
- cuts: $p_T^{j_1} > 80\,\text{GeV}, \quad p_T^{j_2} > 40\,\text{GeV}, \quad |\eta_j| < 4.7,$
  $\eta_{j_1} \cdot \eta_{j_2} < 0, \quad |\Delta\eta_{jj}| > 4.0, \quad |\Delta\phi_{jj}| < 1.5,$
  $M_{jj} > 1.3\,\text{TeV}, \quad \not{E}_T > 250\,\text{GeV}, \quad \ldots$
- shape analysis: $M_{jj} > 200\,\text{GeV}, \quad |\Delta\eta_{jj}| > 1.0$

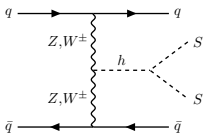
LHC Limits at 13 TeV

- based on CMS – 1809.05937
- search for invisible h decays in VBF: $pp \to h + jj\,,\ h \to \text{inv}$
- $\sqrt{s} = 13\,\text{TeV},\ \mathcal{L} = 35.9\,\text{fb}^{-1}$
- cuts: $p_T^{j_1} > 80\,\text{GeV}, \quad p_T^{j_2} > 40\,\text{GeV}, \quad |\eta_j| < 4.7,$
  $\eta_{j_1} \cdot \eta_{j_2} < 0, \quad |\Delta\eta_{jj}| > 4.0, \quad |\Delta\phi_{jj}| < 1.5,$
  $M_{jj} > 1.3\,\text{TeV}, \quad \not{E}_T > 250\,\text{GeV}, \quad \ldots$
- shape analysis: $M_{jj} > 200\,\text{GeV}, \quad |\Delta\eta_{jj}| > 1.0$
- 95 % CL limits on $\mathcal{B}(h \to \text{inv})$:

$$\mathcal{B}_{\text{inv}} < 58\,\% \quad \text{(cut-and-count)} \qquad \mathcal{B}_{\text{inv}} < 33\,\% \quad \text{(shape)}$$

Reinterpretation

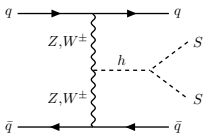
$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\, \Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$



Reinterpretation

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\, \Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

off-shell Higgs invariant mass

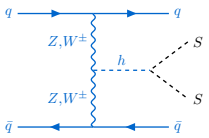


Reinterpretation

off-shell Higgs invariant mass

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\, \Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

off-shell production cross-section



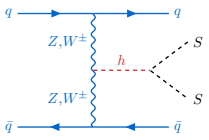
Reinterpretation

off-shell Higgs invariant mass

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\, \Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

off-shell production cross-section

Higgs boson propagator



Reinterpretation

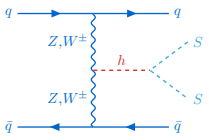
off-shell Higgs invariant mass

invisible decay of off-shell Higgs

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\, \Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

off-shell production cross-section

Higgs boson propagator



Reinterpretation

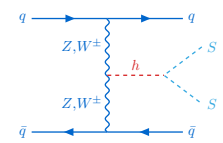
off-shell Higgs invariant mass

invisible decay of off-shell Higgs

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\,\Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

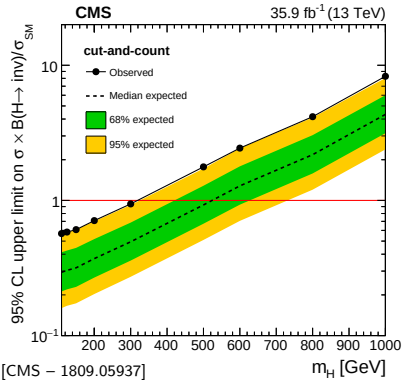
off-shell production cross-section

Higgs boson propagator



- use limits on $\mu_{\mathcal{H}} = \sigma \times \mathcal{B}(\mathcal{H} \to \text{inv}) / \sigma_{\text{SM}}$ for additional Higgs boson with mass $m_{\mathcal{H}}$
- cut-and-count: $\mu_{\mathcal{H}}^{95\%}(m_{\mathcal{H}}) = \dfrac{\sigma_{\text{inv}}^{95\%}}{\sigma_h(q^2 = m_{\mathcal{H}}^2)}$

$$\int \frac{\mathrm{d}q^2}{2\pi}\, \frac{1}{\mu_{\mathcal{H}}^{95\%}(q^2)}\, |P(q^2)|^2\, 2q\,\Gamma_{\text{inv}}(q^2) > 1$$



Reinterpretation

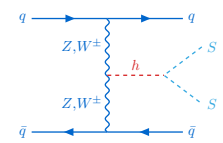
off-shell Higgs invariant mass

invisible decay of off-shell Higgs

$$\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\,\Gamma_{\text{inv}}(q^2)\, \Theta(q^2 - 4m_S^2)$$

off-shell production cross-section

Higgs boson propagator

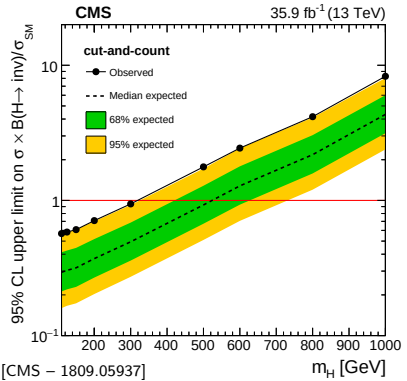


- use limits on $\mu_{\mathcal{H}} = \sigma \times \mathcal{B}(\mathcal{H} \to \text{inv}) / \sigma_{\text{SM}}$ for additional Higgs boson with mass $m_{\mathcal{H}}$
- cut-and-count: $\mu_{\mathcal{H}}^{95\%}(m_{\mathcal{H}}) = \dfrac{\sigma_{\text{inv}}^{95\%}}{\sigma_h(q^2 = m_{\mathcal{H}}^2)}$

$$\int \frac{\mathrm{d}q^2}{2\pi}\, \frac{1}{\mu_{\mathcal{H}}^{95\%}(q^2)}\, |P(q^2)|^2\, 2q\,\Gamma_{\text{inv}}(q^2) > 1$$

- same procedure for shape analysis:

  assumption: M_{jj} and $|\Delta\eta_{jj}|$ distributions only weakly q^2 dependent



Higgs Propagator

Resummed propagator:

$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2$$

Higgs Propagator

Resummed propagator:

$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2$$

close to the resonance:
Breit-Wigner propagator

Higgs Propagator

Resummed propagator:

$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2 \simeq \frac{\pi}{m_P\, \Gamma_{\text{tot}}}\, \delta\left(q^2 - m_P^2\right)$$

close to the resonance: Breit-Wigner propagator

NWA: $\Gamma_{\text{tot}} \ll m_P$

Higgs Propagator

Resummed propagator:

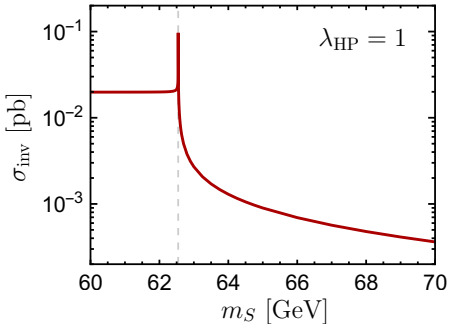
$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2 \simeq \frac{\pi}{m_P\, \Gamma_{\text{tot}}}\, \delta\left(q^2 - m_P^2\right)$$

close to the resonance: Breit-Wigner propagator

NWA: $\Gamma_{\text{tot}} \ll m_P$

- fixed-width prescription only works if $\Gamma_{\text{tot}} \sim$ const in the resonance region

  $\Longrightarrow$ fails if large decay channel opens close to resonance, i.e. for $m_S \gtrsim \frac{m_h}{2}$, $\lambda_{\text{HP}} \gtrsim 0.1$



Higgs Propagator

Resummed propagator:

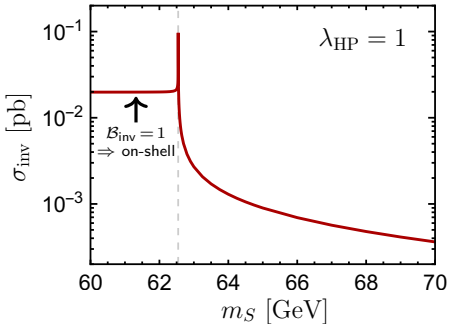
$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2 \simeq \frac{\pi}{m_P\, \Gamma_{\text{tot}}}\, \delta\left(q^2 - m_P^2\right)$$

close to the resonance: Breit-Wigner propagator

NWA: $\Gamma_{\text{tot}} \ll m_P$

- fixed-width prescription only works if $\Gamma_{\text{tot}} \sim$ const in the resonance region

  $\Longrightarrow$ fails if large decay channel opens close to resonance, i.e. for $m_S \gtrsim \frac{m_h}{2}$, $\lambda_{\text{HP}} \gtrsim 0.1$



Higgs Propagator

Resummed propagator:

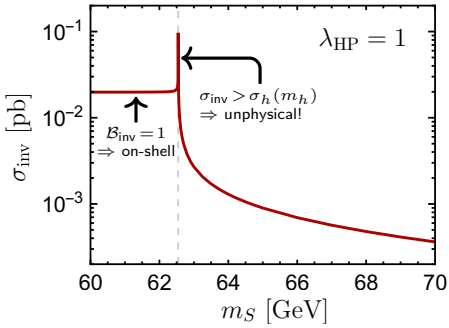
$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2 \simeq \frac{\pi}{m_P\, \Gamma_{\text{tot}}}\, \delta\left(q^2 - m_P^2\right)$$

close to the resonance: Breit-Wigner propagator

NWA: $\Gamma_{\text{tot}} \ll m_P$

- fixed-width prescription only works if $\Gamma_{\text{tot}} \sim$ const in the resonance region

  $\Longrightarrow$ fails if large decay channel opens close to resonance, i.e. for $m_S \gtrsim \frac{m_h}{2}$, $\lambda_{\text{HP}} \gtrsim 0.1$



Higgs Propagator

Resummed propagator:

$$\left|P(q^2)\right|^2 = \left|\frac{i}{q^2 - m_R^2 + \Sigma(q^2) + i\varepsilon}\right|^2 \simeq \left|\frac{i}{q^2 - m_P^2 + i\, m_P\, \Gamma_{\text{tot}}}\right|^2 \simeq \frac{\pi}{m_P\, \Gamma_{\text{tot}}}\, \delta\left(q^2 - m_P^2\right)$$

close to the resonance: Breit-Wigner propagator

NWA: $\Gamma_{\text{tot}} \ll m_P$

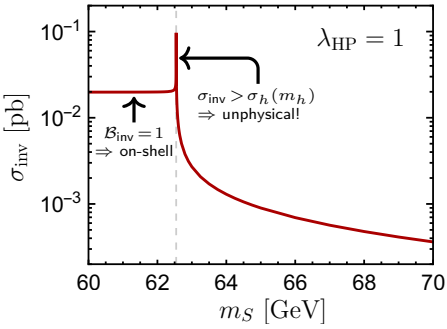
- fixed-width prescription only works if $\Gamma_{\text{tot}} \sim$ const in the resonance region

  $\Longrightarrow$ fails if large decay channel opens close to resonance, i.e. for $m_S \gtrsim \frac{m_h}{2}$, $\lambda_{\text{HP}} \gtrsim 0.1$

- use running-width propagator:

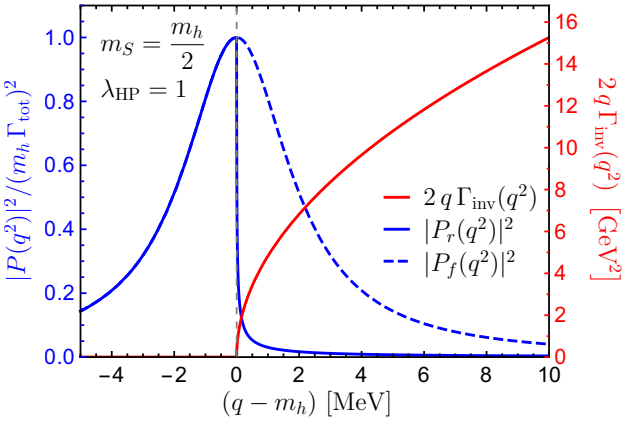
$$P_r(q^2) = \frac{i}{q^2 - m_h^2 + i\,\sqrt{q^2}\,\Gamma_{\text{tot}}(q^2)}$$

here: $\Gamma_{\text{tot}}(q^2) = \Gamma_h^{\text{SM}} + \Gamma_{\text{inv}}(q^2)$



Running Width vs. Fixed Width at $m_S \simeq m_h/2$

Problem: $2q\,\Gamma_{\text{inv}}(q^2)$ grows rapidly for q^2 slightly above $(2m_S)^2$, but fixed-width propagator does not know about the opening invisible channel



Recall: $\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\, \sigma_h(q^2)\, |P(q^2)|^2\, 2q\,\Gamma_{\text{inv}}(q^2)$

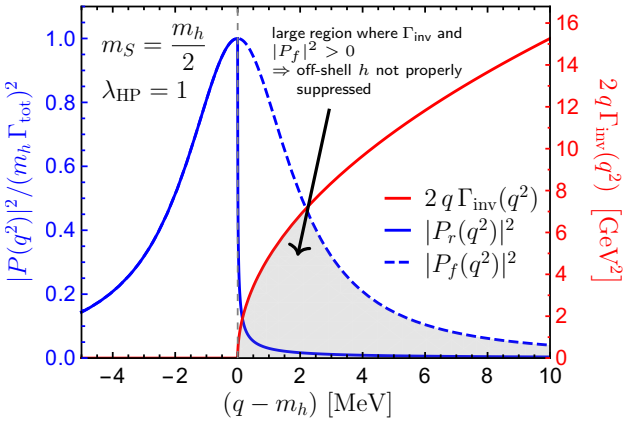
Running Width vs. Fixed Width at $m_S \simeq m_h/2$

Problem: $2q\,\Gamma_{\text{inv}}(q^2)$ grows rapidly for q^2 slightly above $(2m_S)^2$, but fixed-width propagator does not know about the opening invisible channel

consider $2q\,\Gamma_{\text{inv}}(q^2)\,|P(q^2)|^2$ just above resonance ($q^2 \approx m_h^2$):

fixed width:

$$\frac{2\,q\,\Gamma_{\text{inv}}(q^2)}{m_h^2\,\Gamma_{\text{tot}}^2(m_h^2)} \gg 1$$



Recall: $\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\,\sigma_h(q^2)\,|P(q^2)|^2\,2q\,\Gamma_{\text{inv}}(q^2)$

Running Width vs. Fixed Width at $m_S \simeq m_h/2$

Problem: $2q\,\Gamma_{\text{inv}}(q^2)$ grows rapidly for q^2 slightly above $(2m_S)^2$, but fixed-width propagator does not know about the opening invisible channel

consider $2q\,\Gamma_{\text{inv}}(q^2)\,|P(q^2)|^2$ just above resonance ($q^2 \approx m_h^2$):

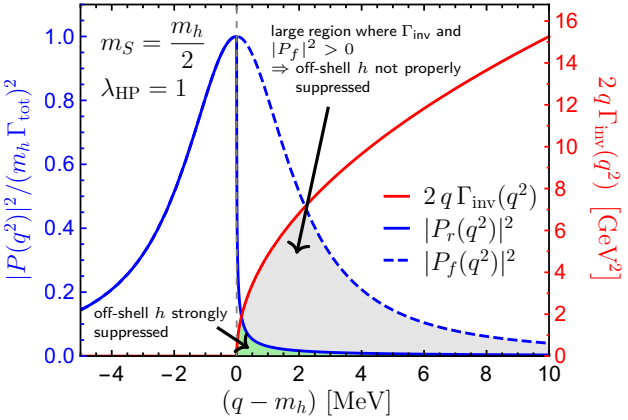
fixed width:

$$\frac{2\,q\,\Gamma_{\text{inv}}(q^2)}{m_h^2\,\Gamma_{\text{tot}}^2(m_h^2)} \gg 1$$

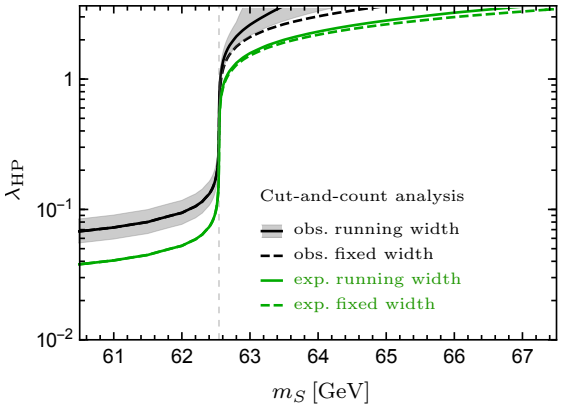
running width:

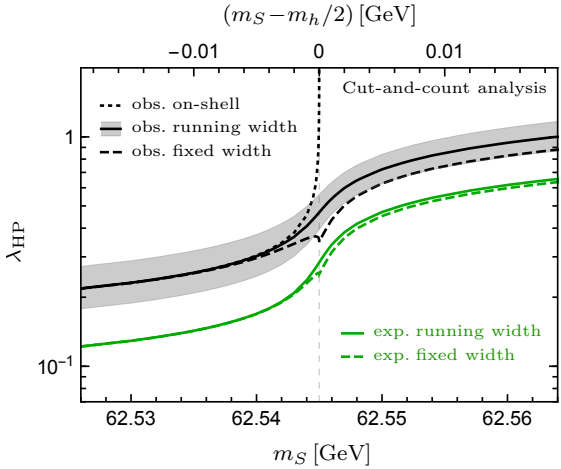
$$\frac{2\,q\,\Gamma_{\text{inv}}(q^2)}{q^2\,\Gamma_{\text{tot}}^2(q^2)} \sim \frac{2}{q\,\Gamma_{\text{inv}}(q^2)}$$

Recall: $\sigma_{\text{inv}} = \int \frac{\mathrm{d}q^2}{2\pi}\,\sigma_h(q^2)\,|P(q^2)|^2\,2q\,\Gamma_{\text{inv}}(q^2)$



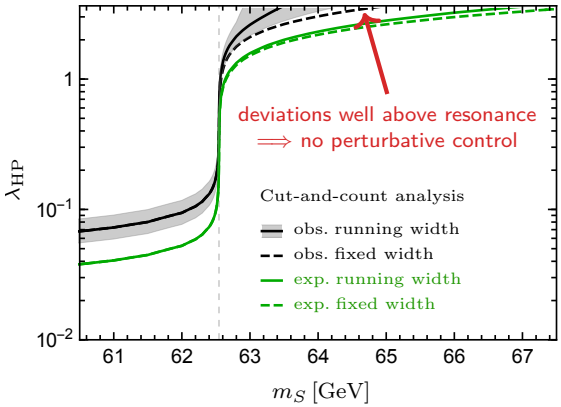
13 TeV Results – Cut and Count

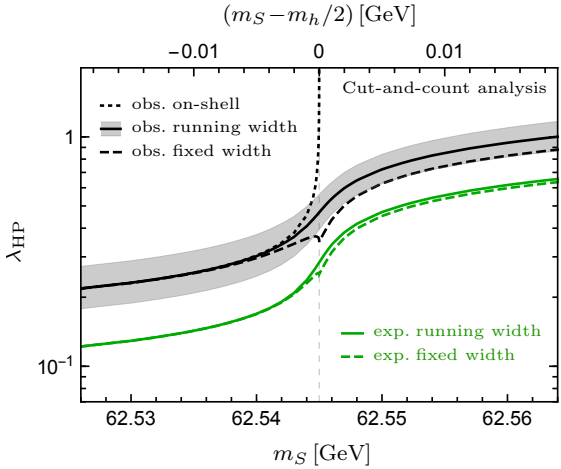




observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 58\,\%\ (30\,\%)$ [CMS – 1809.05937]

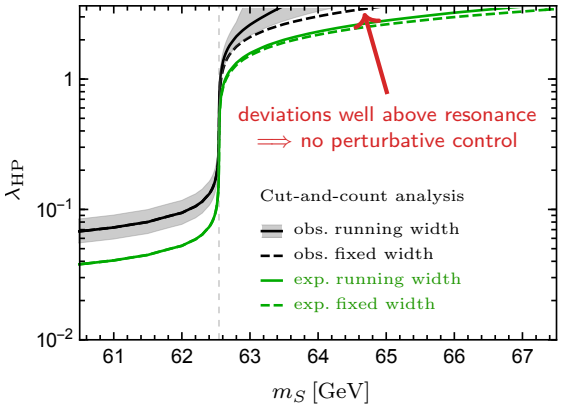
13 TeV Results – Cut and Count

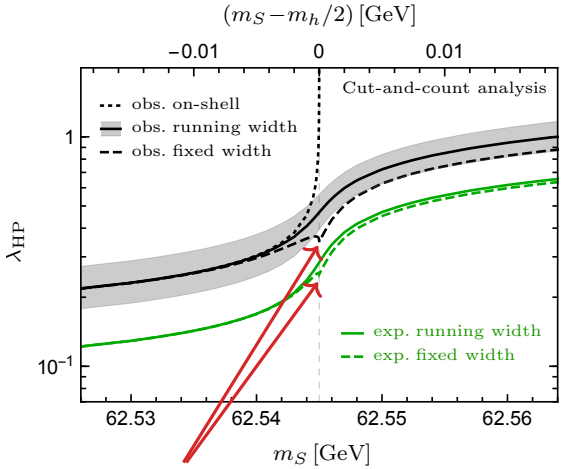




observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 58\,\%\ (30\,\%)$ [CMS – 1809.05937]

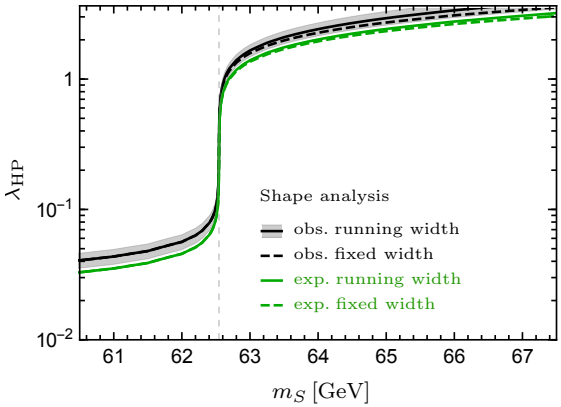
13 TeV Results – Cut and Count

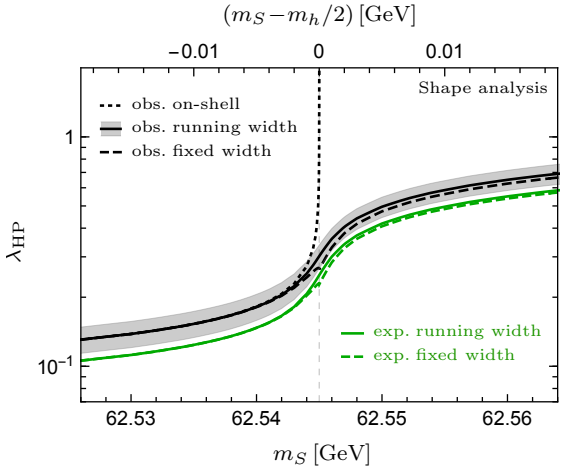




observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 58\,\%\ (30\,\%)$ [CMS – 1809.05937]

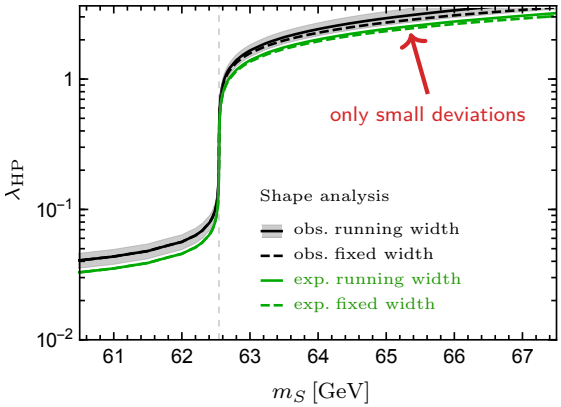
13 TeV Results – Shape Analysis

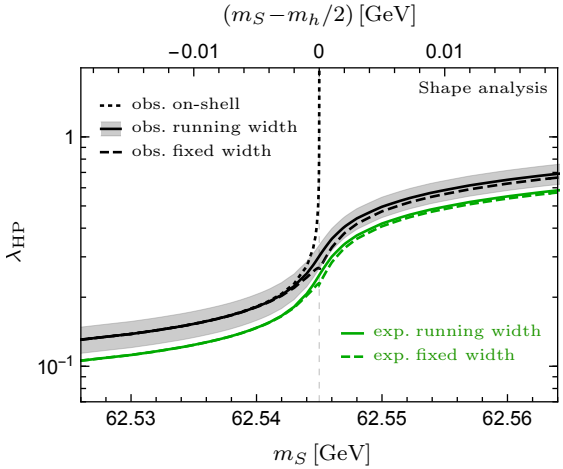




observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 33\,\%\ (25\,\%)$ [CMS – 1809.05937]

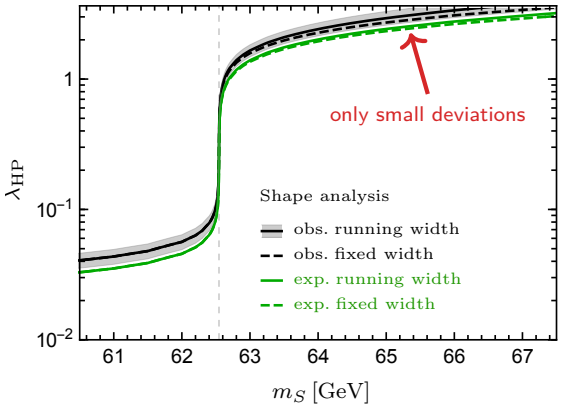
13 TeV Results – Shape Analysis

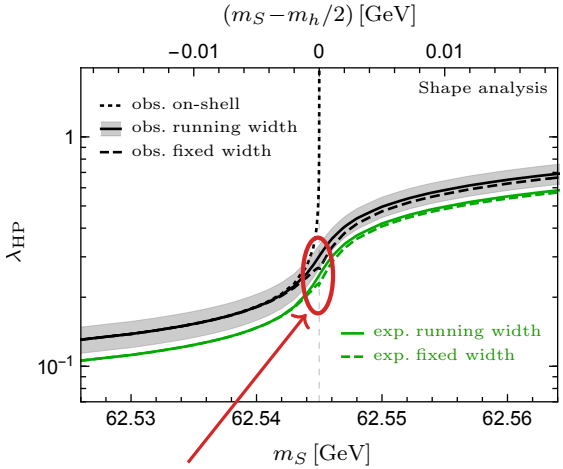




observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 33\,\%\ (25\,\%)$ [CMS – 1809.05937]

13 TeV Results – Shape Analysis





smaller couplings $\Longrightarrow$ smaller effect

observed (expected) limits: $\mathcal{B}(h \to \text{inv}) < 33\,\%\ (25\,\%)$ [CMS – 1809.05937]

HL- and HE-LHC Projections

- HL-LHC: $\sqrt{s} = 14\,\text{TeV}, \quad \mathcal{L} = 3\,\text{ab}^{-1}$ [CMS-PAS-FTR-18-016]

  14 TeV projections for invisible h in VBF by CMS: $\mathcal{B}(h \to \text{inv}) < 3.8\,\%$

  - higher M_{jj} and lower $\not{E}_T$ cut: $M_{jj} > 2.5\,\text{TeV}, \quad \not{E}_T > 190\,\text{GeV}$
  - provides prediction for on-shell Higgs production and background events
  - includes systematic uncertainties

  $\Longrightarrow$ still needed: cross section for off-shell/additional Higgs boson

HL- and HE-LHC Projections

- HL-LHC: $\sqrt{s} = 14\,\text{TeV}, \quad \mathcal{L} = 3\,\text{ab}^{-1}$ [CMS-PAS-FTR-18-016]

  14 TeV projections for invisible h in VBF by CMS: $\mathcal{B}(h \to \text{inv}) < 3.8\,\%$
  - higher M_{jj} and lower $\not{E}_T$ cut: $M_{jj} > 2.5\,\text{TeV}, \quad \not{E}_T > 190\,\text{GeV}$
  - provides prediction for on-shell Higgs production and background events
  - includes systematic uncertainties

  $\Longrightarrow$ still needed: cross section for off-shell/additional Higgs boson

- HE-LHC: $\sqrt{s} = 27\,\text{TeV}, \ \mathcal{L} = 15\,\text{ab}^{-1}$
  - generate signal (on/off-shell) and background events $\longrightarrow$ MC simulation
  - determine sensitivity including systematics $\longrightarrow$ extracted from HL-LHC
  - optimize M_{jj} cut $\longrightarrow$ $M_{jj} > 6\,\text{TeV}$

Systematic Uncertainties

- 95 % CL limit:

$$\frac{S}{\sqrt{S + B + \left(\sigma_B^{\text{sys}}\, B\right)^2}} = 1.96$$

Systematic Uncertainties

- 95 % CL limit:

$$\frac{S}{\sqrt{S + B + \left(\sigma_B^{\text{sys}}\, B\right)^2}} = 1.96$$

- model for systematic uncertainties:

$$\sigma_B^{\text{sys}} = \sqrt{f/B + \left(\sigma_B^{\text{ind}}\right)^2}$$

scales with $1/\mathcal{L}$
e.g. data-driven background determination

luminosity independent
e.g. transfer factors from control to signal region

Systematic Uncertainties

- 95 % CL limit:

$$\frac{S}{\sqrt{S + B + \left(\sigma_B^{\text{sys}}\, B\right)^2}} = 1.96$$

- model for systematic uncertainties:

$$\sigma_B^{\text{sys}} = \sqrt{f/B + \left(\sigma_B^{\text{ind}}\right)^2}$$

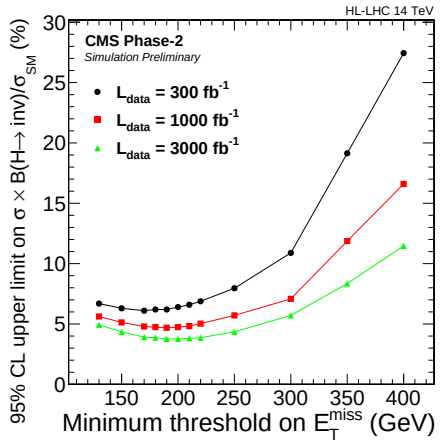
scales with $1/\mathcal{L}$
e.g. data-driven background determination

luminosity independent
e.g. transfer factors from control to signal region

- extract parameters from limits for different $\mathcal{L}$:

$$f = 1.5 \qquad \sigma_B^{\text{ind}} = 1.3\,\%$$

- use same parameters for HE-LHC projections



[CMS-PAS-FTR-18-016]

14 and 27 TeV Results

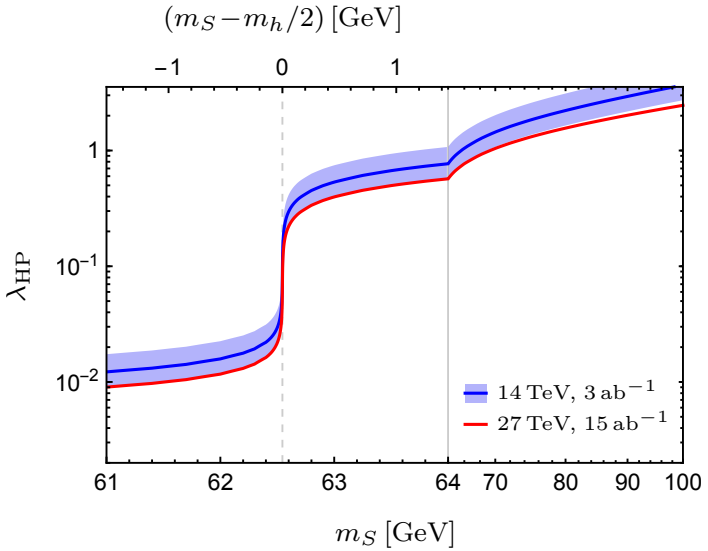
- at $m_S = m_h/2$:

  HL-LHC: $\lambda_{\text{HP}} < 0.090$

  HE-LHC: $\lambda_{\text{HP}} < 0.067$

  $\Longrightarrow$ no visible effect of running vs. fixed width

- HE-LHC: $\mathcal{B}(h \to \text{inv}) \leq 2.1\,\%$



Summary

- VBF promising channel to search for Higgs portal DM
- special attention: Higgs resonance $m_S \simeq m_h/2$

  $\Longrightarrow$ requires running-width propagator!

  fixed-width calculation overestimates exclusion reach by 30 % (15 %) for 13 TeV cut-and-count (shape) analysis
- limits on λ_{HP}: $m_S =$ 61 GeV $m_h/2$ 64 GeV

LHC:	0.04	0.3	2.5
HL-LHC:	0.01	0.09	0.8
HE-LHC:	0.009	0.07	0.6

- limits on $\mu_{\mathcal{H}}$ and λ_{HP} are available as supplementary material to [1912.08472]

Summary

- VBF promising channel to search for Higgs portal DM
- special attention: Higgs resonance $m_S \simeq m_h/2$

  $\Longrightarrow$ requires running-width propagator!

  fixed-width calculation overestimates exclusion reach by 30 % (15 %) for 13 TeV cut-and-count (shape) analysis
- limits on λ_{HP}: $m_S =$ 61 GeV $m_h/2$ 64 GeV

LHC:	0.04	0.3	2.5
HL-LHC:	0.01	0.09	0.8
HE-LHC:	0.009	0.07	0.6

- limits on $\mu_{\mathcal{H}}$ and λ_{HP} are available as supplementary material to [1912.08472]

Thank you for your attention!

Backup

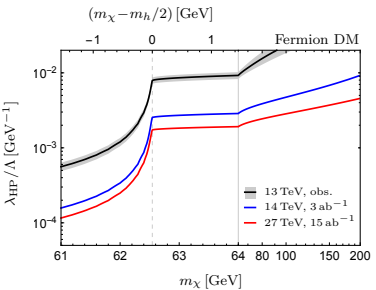
Fermion, Vector, and Tensor Dark Matter

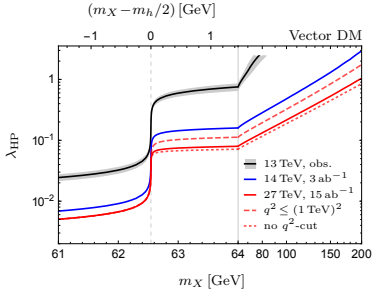
other choices for DM candidate:

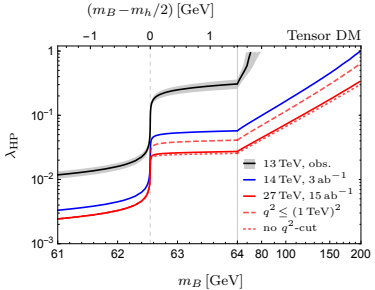
- Majorana fermion χ $\quad \mathcal{L}_{\rm HP} = -\dfrac{\lambda_{\rm HP}}{\Lambda}\,\Phi^\dagger\Phi\,\bar{\chi}\chi$
- vector X^μ $\quad \mathcal{L}_{\rm HP} = -\dfrac{\lambda_{\rm HP}}{2}\,\Phi^\dagger\Phi\,X^\mu X_\mu$
- anti-symmetric tensor $B^{\mu\nu}$ $\quad \mathcal{L}_{\rm HP} = -\dfrac{\lambda_{\rm HP}}{2}\,\Phi^\dagger\Phi\,B^{\mu\nu}B_{\mu\nu}$

Kanemura et al. – 1005.5651
Cata, Ibarra – 1404.0432
Endo, Takaesu – 1407.6882

not UV complete!







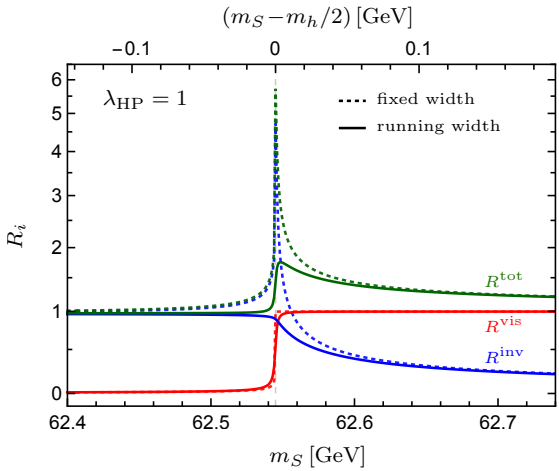
Running Width Propagator

Consider $R_i^X \simeq \dfrac{\sigma_i^X}{\sigma_h(m_h^2)}$:

$$R_f^X = \int \frac{\mathrm{d}q^2}{2\pi} \frac{2q\,\Gamma_X(q^2)}{(q^2 - m_h^2)^2 + m_h^2 \Gamma_{\text{tot}}^2(m_h^2)}$$

$$R_r^X = \int \frac{\mathrm{d}q^2}{2\pi} \frac{2q\,\Gamma_X(q^2)}{(q^2 - m_h^2)^2 + q^2 \Gamma_{\text{tot}}^2(q^2)}$$

- fixed width: (for $m_S \simeq m_h/2$)
  σ_f^{tot} not related to $\sigma_h(m_h^2)$ any more
- running width:
  smooth transition between on- and off-shell region



MC Simulation

- tool chain: MadGraph5 $\longrightarrow$ PYTHIA8 $\longrightarrow$ Delphes
- simulate VBF h production
  ($pp \to \mathcal{H} + 2$ jets)
  at LO for $m_{\mathcal{H}} = 100\,\text{GeV} - 1\,\text{TeV}$
- ggF contribution:

  rescale to on-shell CMS prediction

  (also: NLO/detector effects)
  - 13 TeV : $\sigma_h^{\text{CMS}}/\sigma_h^{\text{MC}} = 1.46$
  - 14 TeV : $\sigma_h^{\text{CMS}}/\sigma_h^{\text{MC}} = 1.54$ ← also for HE-LHC
- background at 27 TeV:

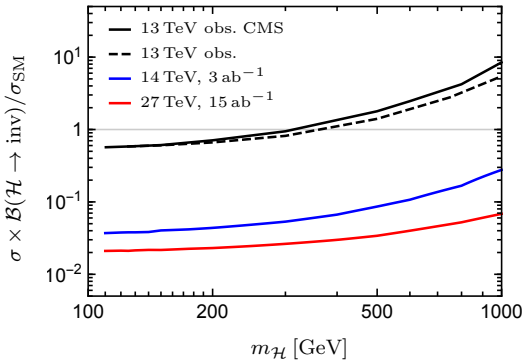
  MC simulation of $Z/W + 2-3$ jets, rescaled based on HL-LHC predictions

MC Simulation

- tool chain: MadGraph5 $\longrightarrow$ PYTHIA8 $\longrightarrow$ Delphes
- simulate VBF h production
  ($pp \to \mathcal{H} + 2$ jets)
  at LO for $m_{\mathcal{H}} = 100\,\text{GeV} - 1\,\text{TeV}$
- ggF contribution:

  rescale to on-shell CMS prediction

  (also: NLO/detector effects)
  - 13 TeV : $\sigma_h^{\text{CMS}}/\sigma_h^{\text{MC}} = 1.46$
  - 14 TeV : $\sigma_h^{\text{CMS}}/\sigma_h^{\text{MC}} = 1.54$ ← also for HE-LHC

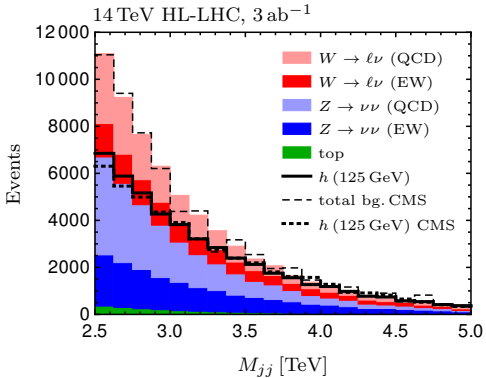


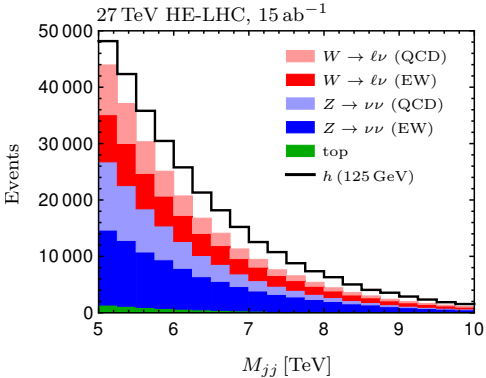
- background at 27 TeV:

  MC simulation of $Z/W + 2-3$ jets, rescaled based on HL-LHC predictions

27 TeV Background Predictions

- MC simulation: $Z/W + 2$ or 3 jets using MLM merging
- rescale background contributions based on 14 TeV CMS predictions
- top + jets included in W + jets rescaling





- optimized M_{jj} cut for $m_h = 125.09$ GeV $\implies$ $M_{jj} > 6$ TeV