Jet Vetoes Interfering with H$\to$ WW

Ian Moult

Massachusetts Institute of Technology

With **Iain Stewart** : 1404.*XXXX*

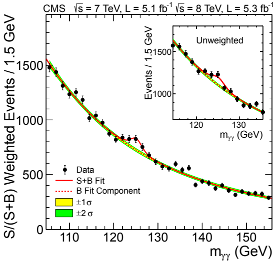
SCET 2014

Outline

1. Motivation: Off-Shell Effects and the Higgs Width
2. Jet Vetoes and Off-shell Effects
3. $gg \to H \to WW$: Resummation for Signal-Background Interference
4. Jet Vetoes Interfere with Higgs Width Bounds

Motivation

- Higgs physics has entered a precision era!
- Higgs couplings and width are a sensitive probe of BSM physics.
- Focus has been on rate measurements in the Narrow Width Approximation (NWA):



$$\sigma_{\text{nwa}} = \sigma_{i\to H}(\hat{s} = m_H^2)\frac{\Gamma_{H\to f}}{\Gamma_H}$$

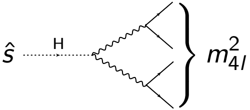
- In terms of couplings and width:

$$\sigma_{\text{nwa}} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \qquad \Longrightarrow \quad \text{Invariant under } g \to \xi g, \quad \Gamma_H \to \xi^4 \Gamma_H$$

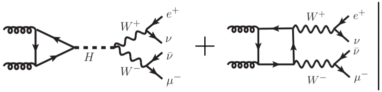
- Due to ξ, impossible to disentangle Higgs width from Higgs couplings without further assumptions.

Off-Shell Effects in Vector Boson Final States

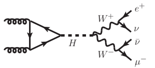
- $\Gamma_H^{SM} \simeq 4MeV$, but for decays to massive vector bosons there are non-negligible contributions from $m_{4l} \gg m_H$.



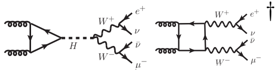
- Can be removed by cuts in Higgs searches so that σ^{nwa} is accurate.
- I will focus on these contributions for $gg \to H \to WW$. Two topologies contribute at LO:

$\sigma \sim \Big|$  $\Big|^2$

- Two contributions depend on the Higgs properties:

$\sigma_H \sim \Big|$  $\Big|^2$

Higgs Mediated

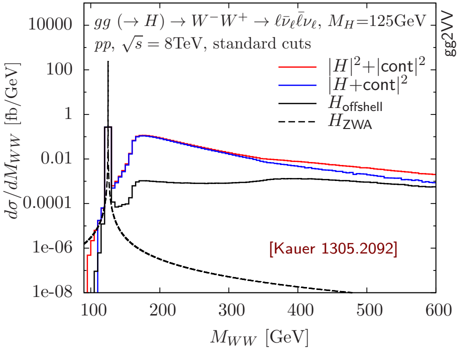
$\sigma_I \sim 2\text{Re}\Big($  $^\dagger\Big)$

Signal-Background Interference

- Remaining term contributes to background.

Off-Shell Effects in Vector Boson Final States

- Off-Shell effects give $\sim 10\%$ contribution to total integrated cross section.



- In the far off-shell region, signal background interference gives the largest contribution involving the Higgs. Its resummation has not been studied, but is required for a description of the off-shell cross-section with a jet veto.

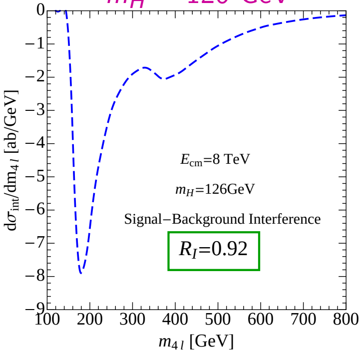
Signal-Background Interference

[Campbell, Ellis, Williams 1107.5569]

- Much smaller total cross section than Higgs mediated contribution. To get an idea of the size, consider: $R_I = \frac{\int dm_{4l}(\sigma_H+\sigma_I)}{\int dm_{4l}\ \sigma_H}$
- Interference comes entirely from above $m_{4l} = 2m_W$.

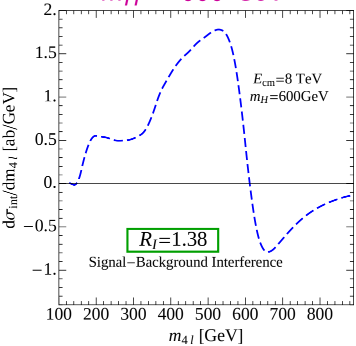
Small for Light Higgs

$m_H = 126$ GeV



Large for Heavy Higgs

$m_H = 600$ GeV



Possible to remove interference by cuts for a light Higgs.

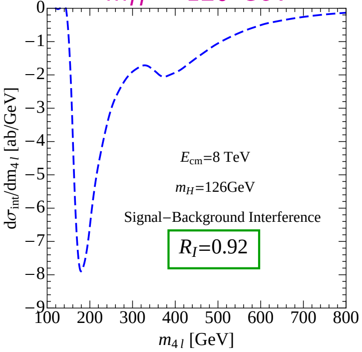
Signal-Background Interference

[Campbell, Ellis, Williams 1107.5569]

- Much smaller total cross section than Higgs mediated contribution. To get an idea of the size, consider: $R_I = \frac{\int dm_{4l}(\sigma_H+\sigma_I)}{\int dm_{4l}\ \sigma_H}$
- Interference comes entirely from above $m_{4l} = 2m_W$.

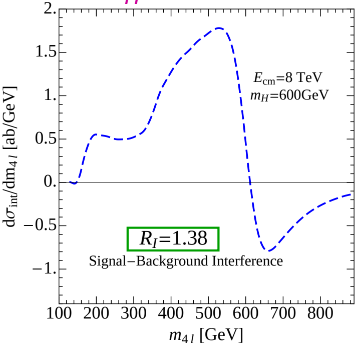
Small for Light Higgs

$m_H = 126$ GeV



Large for Heavy Higgs

$m_H = 600$ GeV



Connection to the Higgs Width

Small, But Interesting!

[Caolo, Melnikov 1307.4935]
[Campbell, Ellis, Williams 1311.3589,1312.1628]

- Off-Shell Contributions are independent of the Higgs width:

$$\frac{1}{(\hat{s}-m_H^2)+i\Gamma_H m_H} \xrightarrow{\hat{s}\gg m_H} \frac{1}{(\hat{s}-m_H^2)}$$

$\Longrightarrow$ Provides sensitivity to three distinct scalings

$$\sigma_{\rm nwa} \sim \frac{g_i^2 g_f^2}{\Gamma_H}, \qquad \sigma_I \sim g_i g_f, \qquad \sigma_H^{\text{off-shell}} \sim g_i^2 g_f^2,$$

allowing one to disentangle coupling and width information.

- Relies on ability to experimentally separate components
  - $H \to ZZ$: easy, $\hat{s}$ is measured.
  - $H \to WW$: use M_T

$$M_T^2 = (E_T^{\rm miss} + E_T^{ll})^2 + |\mathbf{p}_\mathbf{T}^{\mathbf{ll}} + \mathbf{E}_\mathbf{T}^{\mathbf{miss}}|^2$$

Current Status

- LHC measurements of σ_{nwa} are consistent with the SM. This has fixed the scaling of large new physics contributions:

Recall:

$$\sigma_{\text{nwa}} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \qquad \Longrightarrow \quad \text{Invariant under } g = \xi g^{\text{SM}}, \quad \Gamma_H = \xi^4 \Gamma_H^{\text{SM}}$$

Rewriting ξ in terms of Γ_H, we find that the off-shell Higgs mediated and signal-background interference cross sections scale like:

$$\sigma_I = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}} \sigma_I^{\text{SM}}, \qquad \sigma_H^{\text{off-shell}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} \sigma_{H,\text{SM}}^{\text{off-shell}}$$

Current Status

- LHC measurements of σ_{nwa} are consistent with the SM. This has fixed the scaling of large new physics contributions:

Recall:

$$\sigma_{\text{nwa}} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \qquad \Longrightarrow \quad \text{Invariant under } g = \xi g^{\text{SM}}, \quad \Gamma_H = \xi^4 \Gamma_H^{\text{SM}}$$

Rewriting ξ in terms of Γ_H, we find that the off-shell Higgs mediated and signal-background interference cross sections scale like: Sensitive to Γ_H !

$$\sigma_I = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}\,\sigma_I^{\text{SM}}, \qquad \sigma_H^{\text{off-shell}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}\,\sigma_{H,\text{SM}}^{\text{off-shell}}$$

Current Status

- LHC measurements of σ_{nwa} are consistent with the SM. This has fixed the scaling of large new physics contributions:

$$\sigma_I = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}\sigma_I^{\text{SM}}, \qquad \sigma_H^{\text{off-shell}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}\sigma_{H,\text{SM}}^{\text{off-shell}}$$

- Using current data in both $H \to ZZ$ and $H \to WW$:

Bounds of $\Gamma_H \sim 10 - 25\ \Gamma_H^{\text{SM}}$ from off-shell region compared to $\Gamma_H \sim 1000\ \Gamma_H^{\text{SM}}$ from on-shell analysis.

[CMS-PAS-HIG-14-002]
[CMS arXiv:1312.5353]
[Campbell, Ellis, Williams 1312.1628]

- Motivates dedicated experimental studies and improved theoretical understanding of the far off-shell region, especially in the presence of realistic experimental cuts:

Current calculation LO and ignores Jet veto

Current Status

- LHC measurements of σ_{nwa} are consistent with the SM. This has fixed the scaling of large new physics contributions:

$$\sigma_I = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}\sigma_I^{\text{SM}}, \qquad \sigma_H^{\text{off-shell}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}\sigma_{H,\text{SM}}^{\text{off-shell}}$$

- Using current data in both $H \to ZZ$ and $H \to WW$:

Bounds of $\Gamma_H \sim 10 - 25\ \Gamma_H^{\text{SM}}$ from off-shell region compared to $\Gamma_H \sim 1000\ \Gamma_H^{\text{SM}}$ from on-shell analysis.

[CMS-PAS-HIG-14-002]
[CMS arXiv:1312.5353]
[Campbell, Ellis, Williams 1312.1628]

- Motivates dedicated experimental studies and improved theoretical understanding of the far off-shell region, especially in the presence of realistic experimental cuts:

Current calculation LO and ignores Jet veto

SCET

Jet Vetoes

- Jet Vetoes essential for $H \to WW$ to reduce $\bar{t}t$ background.

  $\Longrightarrow$ Maximum sensitivity in zero jet bin: $p_T^J < p_T^{veto}$

- Places severe constraints on radiation

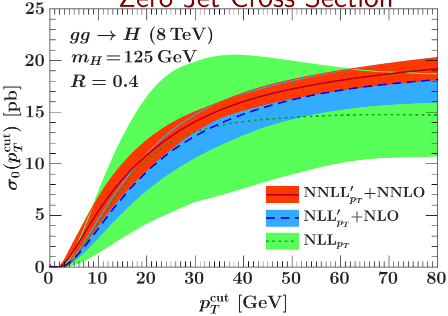
  $\Longrightarrow$ Large logarithms, $\log m_H / p_T^{veto}$, necessitate resummation.

- Well studied for on-shell Higgs production:
  - Treatment of jet alg.

    [Tackmann, Walsh, Zuberi 1206.4312]
    [Ellis, Hornig, Lee, Vermilion, Walsh 1001.0014]
    [Neubert, Becher 1205.3806]
  - $\mathrm{NNLL}'_{p_T} + \mathrm{NNLO}$ accuracy

Figure from: [Stewart, Tackmann, Walsh, Zuberi 1307.1808]
See also: [Becher, Neubert, Rother 1307.0025]
[Banfi, Monni, Salam, Zanderighi 1206.4998]

Zero Jet Cross Section



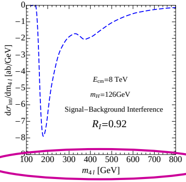
Suppression with decreasing p_T^{veto}

What changes when you go off-shell?

- Consider processes with contributions from a large range of $\hat{s}$.

e.g. Interference in $gg \to H \to WW$

Nontrivial contributions from
$m_{4l} = 160 \to \sim 700$ GeV



- Resum $\log \sqrt{\hat{s}}/p_T^{veto}$: Changes significantly from on-shell to far off-shell contribution

- Basic effects of Jet Veto on zero jet cross section:
  - Modifies differential distributions in $\hat{s}$ or M_T.
  - Inteference and interference cancellations are reshaped.

- Doesn't occur in NWA where cross-section is evaluated at $\hat{s} = m_H^2$.

Factorization Theorem with a p_T^{veto}

- Factorization theorem for exclusive 0-jet bin defined using a cut p_T^{veto} of anti-kt jets in $\mathrm{SCET_{II}}$:

$$\frac{d\sigma(p_T^{veto})}{d\sqrt{\hat{s}}} = \frac{d\sigma_B}{d\sqrt{\hat{s}}} \sum_{i,j} \mathcal{H}_{i,j}(\sqrt{\hat{s}}, \mu)$$

$$\int dY \; B_i(\sqrt{\hat{s}}, p_T^{veto}, R, x_a, \mu, \nu) \times B_j(\sqrt{\hat{s}}, p_T^{veto}, R, x_b, \mu, \nu) S_{i,j}(p_T^{veto}, R, \mu, \nu)$$

$$+ \frac{d\sigma_0^{Rsub}(p_T^{veto}, R)}{d\sqrt{\hat{s}}} + \frac{d\sigma_0^{ns}(p_T^{veto}, R, \mu_{ns})}{d\sqrt{\hat{s}}}$$

Based on:
[Stewart, Tackmann, Walsh, Zuberi 1307.1808]
[Tackmann, Walsh, Zuberi 1206.4312]

- Hard function encodes process dependent hard matrix element. For the case $gg \to H \to WW \to \mu\bar{\nu}_\mu \bar{e}\nu_e$ which I will consider, this will be the focus.
- Beam and Soft functions depend only on measurement and parton identity, and have been previously calculated.

Expansion to NLL

- Quantify general effect of jet veto as a function of $\hat{s}$:

$$E(\hat{s}) = \left(\frac{d\sigma_0(p_T^{veto})}{d\sqrt{\hat{s}}}\right) \Big/ \left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)$$

- Convenient expansion to NLL, in terms of standard QCD objects(with canonical scale choices): [Banfi, Salam, Zanderighi 1203.5773]

$$\sigma_{NLL}(p_T^{veto}) = \int d\hat{s} \int dx_1 dx_2 f_1(x_1, \mu = p_T^{veto}) f_2(x_2, \mu = p_T^{veto}) \times \delta(x_1 x_2 E_{cm}^2 - \hat{s}) |\mathcal{M}(\hat{s})|^2 e^{-K_{NLL}(\sqrt{\hat{s}}/p_T^{veto})}$$

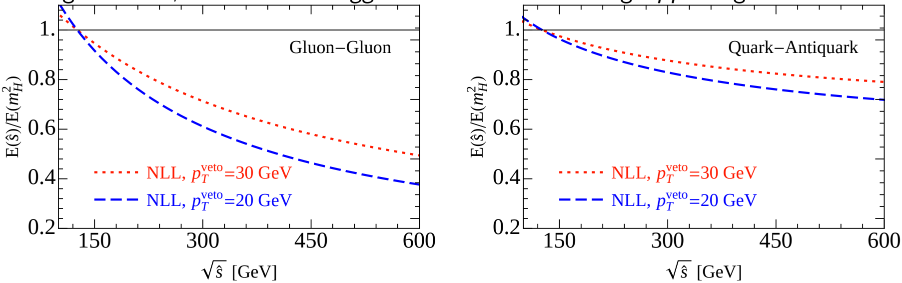
- Use NLL expression to understand basic behavior/dependencies before focusing on the example of $gg \to H \to WW$.

Jet Vetoes and Off-Shell Effects

Jet Veto $\implies$ Strong $\hat{s}$ dependent suppression in the zero jet bin.

Gluon-Gluon Channel
e.g. off-shell, interference for $gg \to H$

Quark-Antiquark Channel
e.g. $q\bar{q}$ background



Jet bins related: $$\frac{d\sigma_{\geq 1}(p_T^{veto})}{d\sqrt{\hat{s}}} = \frac{d\sigma_{\geq 0}}{d\sqrt{\hat{s}}} - \frac{d\sigma_0(p_T^{veto})}{d\sqrt{\hat{s}}}$$

$$\frac{d\sigma_{\geq 1}(p_T^{veto})}{d\sqrt{\hat{s}}} \Big/ \frac{d\sigma_{\geq 0}}{d\sqrt{\hat{s}}} = 1 - E(\hat{s})$$ $\implies$ Migration to inclusive 1-jet bin.

$gg \to H \to WW \to \mu\bar{\nu}_\mu \bar{e}\nu_e$

- Use the phenomenologically interesting case of $gg \to H \to WW \to \mu\bar{\nu}_\mu \bar{e}\nu_e$ to demonstrate the effect of the jet veto on the off-shell cross section.
- Perform an NLL resummation of the off-shell cross-section: Requires both Higgs mediated contribution and signal-background interference.
- Use a hard function that is fully differential in leptonic final state.

  $\Longrightarrow$ Easy to implement realistic cuts.
- Will allow us to comment on the effect of the jet veto on the Higgs width bounds derived from this channel

$gg \to H \to WW \to \mu\bar{\nu}_\mu \bar{e}\nu_e$

Hard Function:

- Use a helicity and color basis in SCET to easily interface with fixed order QCD calculations: [Stewart, Tackmann, Waalewijn 1211.2305]

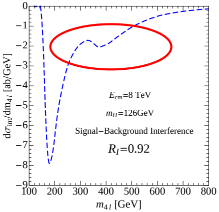
$$\mathcal{O}^{++} = \mathcal{B}^a_{n+}\mathcal{B}^a_{\bar{n}+}\bar{\mu}\gamma^\alpha(1-\gamma_5)\nu_\mu\bar{\nu}_e\gamma_\alpha(1-\gamma_5)e$$
$$\mathcal{O}^{--} = \mathcal{B}^a_{n-}\mathcal{B}^a_{\bar{n}-}\bar{\mu}\gamma^\alpha(1-\gamma_5)\nu_\mu\bar{\nu}_e\gamma_\alpha(1-\gamma_5)e$$

- Higgs is a scalar $\implies \mathcal{O}^{+-} = \mathcal{O}^{-+} = 0$.
- No mixing between helicity structures under RGE.
- Separate Wilson coefficient for continuum, C^C, and Higgs mediated, C^H, contributions. Easy to discuss interference.

$$\mathcal{H}^H = |C^H_{++}|^2 + |C^H_{--}|^2$$
$$\mathcal{H}^{int} = 2\mathrm{Re}\left[C^H_{++}(C^C_{++})^\dagger\right] + 2\mathrm{Re}\left[C^H_{--}(C^C_{--})^\dagger\right]$$

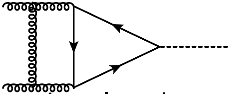
$gg \to H \to WW \to \mu\bar{\nu}_\mu\bar{e}\nu_e$

- Difficult regime for fixed order calculations: Require full dependence on top quark mass

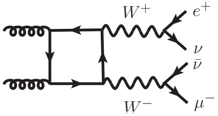


- C^H: Analytic result for two loop virtuals with quark mass dependence known.

[Harlander, Kant 0509189]
[Anastasiou, Beerli, Bucherer, Daleo, Kunszt 0611236]



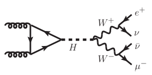
- C^C: Two loop virtuals unknown. Leading (One loop) calculation done by MCFM: Extract C^C_{++}, C^C_{--}



[Campbell, Ellis, Williams 1107.5569]

- Restricted to NLL for Signal-Background interference.

Higgs Mediated Contribution

$\sigma_H \sim \left| \right.$  $\left. \right|^2$

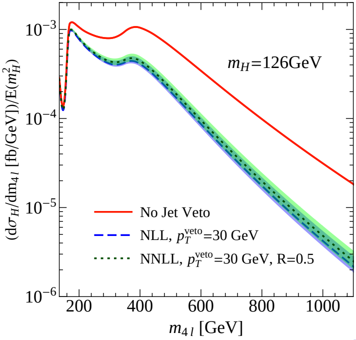
- Use Higgs mediated off-shell contribution to assess impact of NNLL terms:

  $\Longrightarrow$ First sensitive to jet algorithm at NNLL: $\log\left(\sqrt{\hat{s}}/p_T^{veto}\right)\log R$

- Normalize result by suppression at m_H. Focus on modification to the shape.
- Large $\hat{s}$ dependent suppression.
- NNLL, NLL results similar.

  $\Longrightarrow$ NLL captures dominant modification to shape.

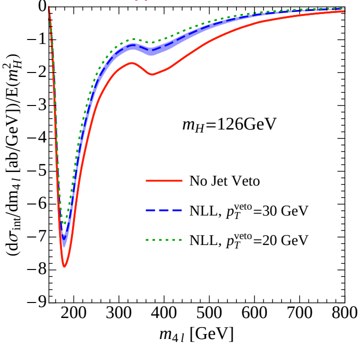
  This is important for interference, where we are restricted to NLL.

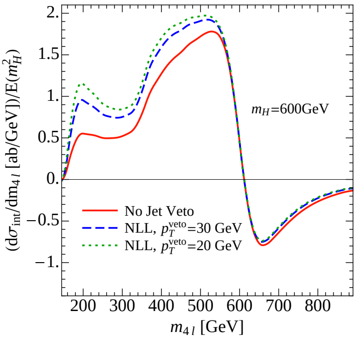


Resummed Predictions for Signal-Background Interference

- Consider effect on two different Higgs masses.
- Normalize the NLL distributions to the jet veto suppression at m_H. Shows the suppression of the interference relative to the on-shell contribution, due to the jet veto: strong $\hat{s}$ dependence.

$m_H = 126$ GeV $\qquad$ $m_H = 600$ GeV



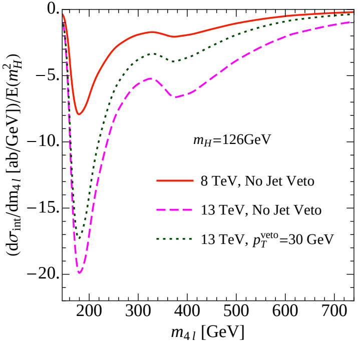


- Jet veto can enhance or suppress relative size of interference.

From 8 TeV to 13 TeV

- At 13 TeV, large increase in gluon luminosity at high $\hat{s}$.
- Enhancement of off-shell effects and of the impact of the jet veto.

$m_H = 126$ GeV



Higgs Width Bounds

Recall three scalings:

[Caolo, Melnikov 1307.4935]
[Campbell, Ellis, Williams 1311.3589,1312.1628]

$$\sigma^{H+I} = \underbrace{A}_{\text{nwa}} + \underbrace{B\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)}_{\text{off-shell Higgs}} + \underbrace{C\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}}_{\text{interference}}$$

A Procedure[CEW]:

- Apply cuts such that B, $C = 0$: $0.75 m_H < M_T < m_H$
- Compute normalization between theory prediction and experiment independent of Γ_H (Originally due to jet veto, and K-factors).
- Apply cuts such that $A = 0$: $M_T > 300\text{GeV}$ to maximize sensitivity to Γ_H.
- Place bounds on the Higgs width using previously calculated normalization.

Relies on accurate theory prediction for the shape of m_{4l} distribution!

NLL result captures this.

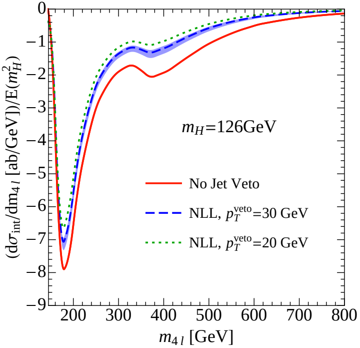
Higgs Width Bounds

- Jet Veto modifies the shape of the differential distribution.
- Zero jet cross-section in far off-shell region reduced by factor of ~ 2 relative to on-shell contribution.

Inclusion of Jet veto effects essential when comparing cross section at widely separated m_{4l}.

Weakens bound on Γ_H by a factor of 2-4.

$m_H = 126$ GeV



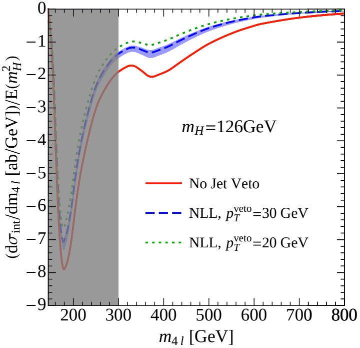
Higgs Width Bounds

- Jet Veto modifies the shape of the differential distribution.
- Zero jet cross-section in far off-shell region reduced by factor of ~ 2 relative to on-shell contribution.

Inclusion of Jet veto effects essential when comparing cross section at widely separated m_{4l}.

Weakens bound on Γ_H by a factor of 2-4.

$m_H = 126$ GeV



Conclusions

- Jet Vetoes have important consequences when studying observables that contribute over a large range of $\hat{s}$. In particular, they reshape differential distributions.
- Large impact on the recent program to extract the Higgs width from off-shell cross section measurements, modifying the bounds by a factor of $2-4$.
- Resummed predictions for the off-shell cross section including signal-background interference allow this region to be used as a sensitive probe of BSM physics.