Jet Vetoes Interfering with H$\rightarrow$ WW

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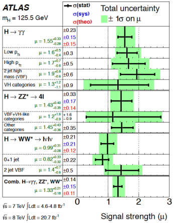
Motivation

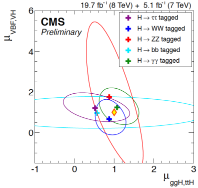
- In the absence of new physics, the focus of the next 100/fb will be on the precision measurements of Higgs properties:

  Most interesting are Couplings and Width.



- Focus of first 25/fb was on-shell rate measurements:

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



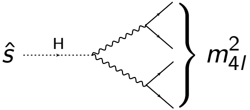
- In terms of couplings and width:

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

- Impossible to disentangle Higgs width from Higgs couplings with on-shell measurements $\Longrightarrow$ must go off-shell! (See also Stefan Liebler)

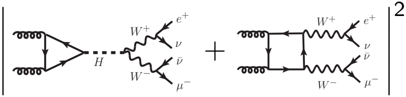
Off-Shell Effects in Vector Boson Final States

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



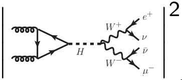
- Focus on these contributions for $gg \to H \to WW$ (similar diagrams for ZZ). Two topologies contribute at LO:

$\sigma \sim$



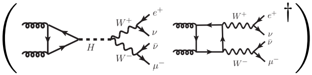
- Two terms depend on the Higgs properties:

$\sigma_H \sim$



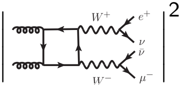
Higgs Mediated

$\sigma_I \sim$ 2Re



Signal-Background Interference

- $\sigma_{WW} \supset$

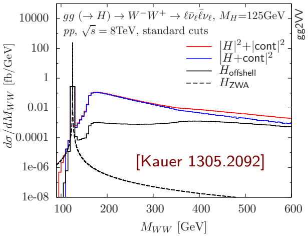


contributes to inclusive $pp \to WW$.

Off-Shell Effects in Vector Boson Final States

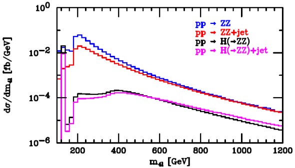
- Off-Shell effects give $\sim 10\%$ contribution to total integrated cross section.

WW

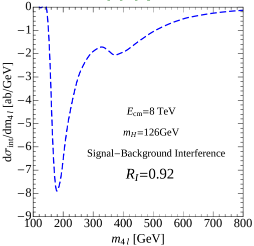


ZZ, *ZZ* + Jet

[Campbell, Ellis, Furlan, Rontsch 1409.1897]



WW



- Interference gives dominant off-shell contribution, and comes entirely from above $m_{4l} = 2m_W$.

$$R_I = \frac{\int dm_{4l}\ (\sigma_H + \sigma_I)}{\int dm_{4l}\ \sigma_H} = 0.92$$

Connection to the Higgs Width

[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 distinct scalings

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

allowing one to disentangle coupling and width information.

- More generally, probes new particle loops over a range of energies.
- Relies on ability to experimentally separate components
    - $H \to ZZ$: easy, $\hat{s}$ is measured.
    - $H \to WW$: use $M_T^2 = (E_T^{\text{miss}} + E_T^{ll})^2 + |\mathbf{p_T^{ll}} + \mathbf{E_T^{miss}}|^2$

Higgs Width

- Extractions of Γ_H are model dependent.
- In a simple model, where only the SM couplings and width are modified as $\Gamma_H = \xi^4 \Gamma_H^{\text{SM}}$, $g = \xi g^{\text{SM}}$ (as used in CMS/ATLAS off-shell studies), the off-shell Higgs mediated and signal-background interference cross sections scale like

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

giving sensitivity to total Higgs width.

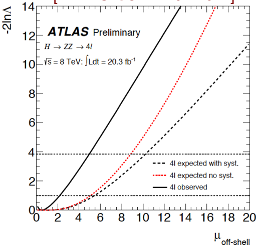
- With the addition of new particles (e.g. colored scalars), relation between on-shell and off-shell cross section is model dependent, but allows for constraints unavailable from on-shell measurements.

[Englert, Spannowsky 1405.0285]

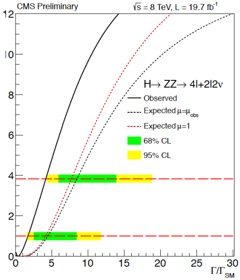
Current Status

- Bounds of $\Gamma_H \sim 5\ \Gamma_H^{SM}$ from off-shell region in ZZ compared to $\Gamma_H \sim 1000\ \Gamma_H^{SM}$ from on-shell analysis.

[ATLAS-CONF-2014-042]



[CMS arXiv:1312.5353]



- HXSWG investigating potential of off-shell measurements.
- Could play a large role in the next 100/fb.
- Motivates improved theoretical understanding of the far off-shell region, especially in the presence of realistic experimental cuts:

  Early theory calculations LO and ignored Jet Veto.
- In this talk, focus on the resummation of jet veto logarithms.
- Another direction is NLO, see: [Campbell, Ellis, Furlan, Rontsch 1409.1897] [Henn, Melnikov, Smirnov 1402.7078] [Caola, Henn, Melnikov, Smirnov 1404.5590]

Jet Vetoes

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

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

- Jet Binning also used in $H \to ZZ$ to maximize sensitivity.
- Places severe constraints on radiation

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

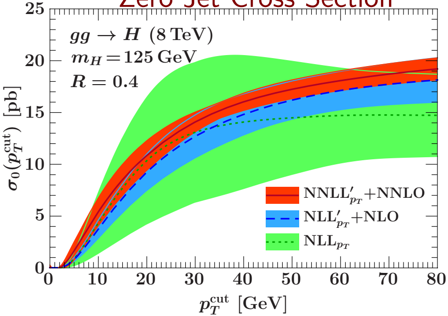
- Well studied for on-shell Higgs production:
  - Treatment of jet alg.

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

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

Suppression with decreasing p_T^{veto}

Zero Jet Cross Section

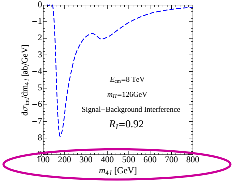


What changes when you go off-shell?

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

e.g. Off-Shell/ Interference in $gg \to H \to WW$

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



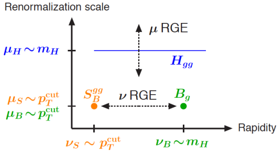
- Resum $\log \sqrt{\hat{s}}/p_T^{veto}$: Changes significantly from on-shell to far off-shell.

$\implies$ Differential distributions in $\hat{s}$ or M_T are reshaped.

- Doesn't occur in NWA where cross-section is evaluated at $\hat{s} = m_H^2$, and the effect of the jet veto is a multiplicative factor.

Factorization Theorem with a p_T^{veto}

- $\log \sqrt{\hat{s}}/p_T^{veto}$ resummed by RG evolution in both virtuality and rapidity in Soft-Collinear Effective Theory (SCET).
- Factorization theorem for exclusive 0-jet bin:



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

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

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

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

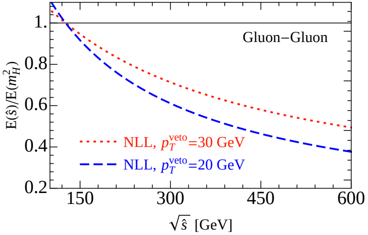
- Hard function encodes process dependent hard matrix element. e.g. $gg \to H \to WW \to \mu \bar{\nu}_\mu \bar{e} \nu_e$.
- Beam and Soft functions depend only on measurement and parton identity.

Jet Vetoes and Off-Shell Effects: Generics

Consider $E(\hat{s}) = \left(\frac{d\sigma_0(p_T^{veto})}{d\sqrt{\hat{s}}}\right) \Big/ \left(\frac{d\sigma}{d\sqrt{\hat{s}}}\right)$: suppression in zero jet bin.

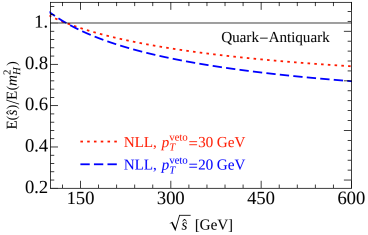
Gluon-Gluon Channel

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.

- Match QCD to SCET helicity operators to easily interface with fixed order QCD calculations: [IM, Stewart, Tackmann, Waalewijn, Forthcoming] [Stewart, Tackmann, Waalewijn 1211.2305]

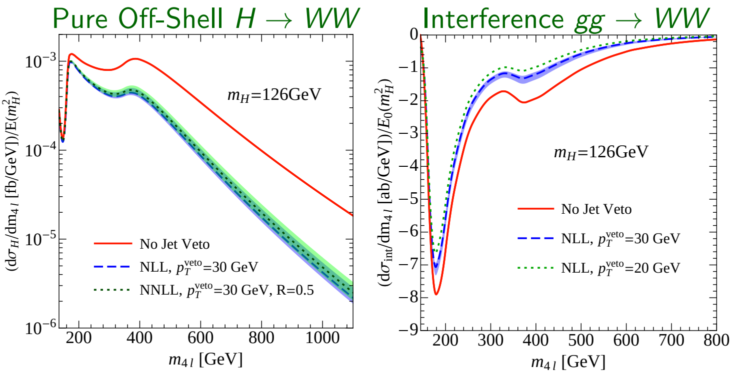
$$\mathcal{O}^{++} = \mathcal{B}^a_{n+}\mathcal{B}^a_{\bar{n}+}\bar{\mu}\gamma^\alpha(1-\gamma_5)\nu_\mu\bar{\nu}_e\gamma_\alpha(1-\gamma_5)e$$
$$\mathcal{O}^{--} = \mathcal{B}^a_{n-}\mathcal{B}^a_{\bar{n}-}\bar{\mu}\gamma^\alpha(1-\gamma_5)\nu_\mu\bar{\nu}_e\gamma_\alpha(1-\gamma_5)e$$

- No mixing between helicity structures under RGE.
- Wilson coefficients are given by (IR finite piece of) color stripped helicity amplitudes. Extract from: [Harlander, Kant 0509189] [Anastasiou, Beerli, Bucherer, Daleo, Kunszt 0611236] [Campbell, Ellis, Williams 1107.5569]
- Fully differential in leptonic final state.

- Similar approach applies to $H \to ZZ$ if jet binning applied.

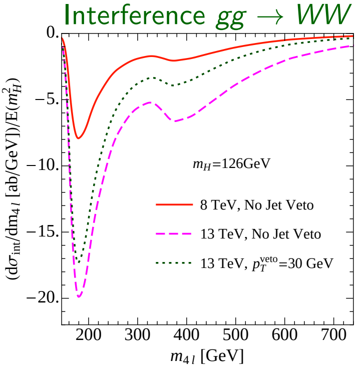
Resummed Predictions for Signal-Background Interference

- Normalize the 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.
- Interference restricted to NLL accuracy, as NLO virtuals unknown.



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.



Higgs Width Bounds

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

Recall three scalings:

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

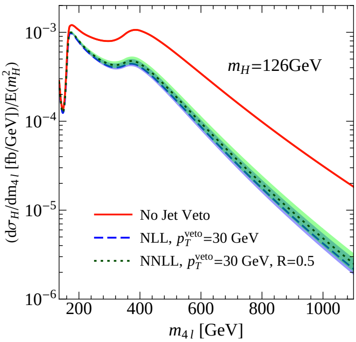
A Procedure [CEW]:

- 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.

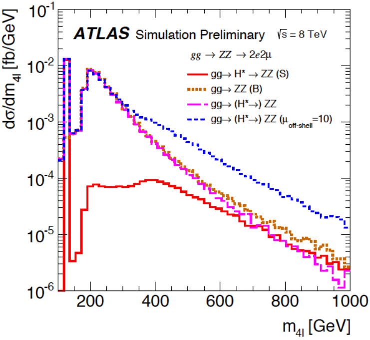
Higgs Width Bounds

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

Pure Off-Shell $H \to WW$



ATLAS Simulation $H \to ZZ$



- Need to be able to distinguish QCD effects from New Physics.

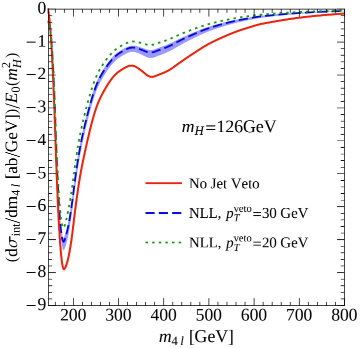
Higgs Width Bounds in $H \to WW$

- 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 or more.

$m_H = 126$ GeV



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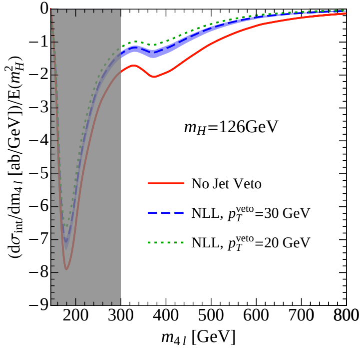


Conclusions

- Jet Vetoes have important consequences when studying observables that contribute over a large range of $\hat{s}$: they reshape differential distributions.
- Large impact on the recent program to extract the Higgs width from off-shell cross section measurements, modifying the predicted bounds by a factor of ~ 2 in $H \to WW$.
- 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 in $H \to WW$, and for more exclusive measurements in $H \to ZZ$.

Backup

Expansion to NLL

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

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

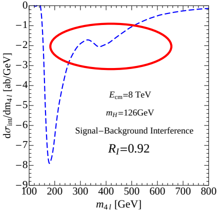
- Convenient expansion to NLL, in terms of standard QCD objects(with canonical scale choices): [Banfi, Salam, Zanderighi 1203.5773]

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

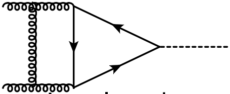
- Use NLL expression to understand basic behavior/dependencies before focusing on the example of $gg \to H \to WW$.

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

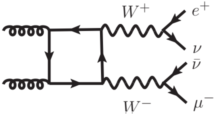
- Difficult regime for fixed order calculations: Require full dependence on top quark mass



- C^H: Analytic result for two loop virtuals with quark mass dependence known.
[Harlander, Kant 0509189]
[Anastasiou, Beerli, Bucherer, Daleo, Kunszt 0611236]



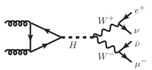
- C^C: Two loop virtuals unknown. Leading (One loop) calculation done by MCFM: Extract C^C_{++}, C^C_{--}



[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:

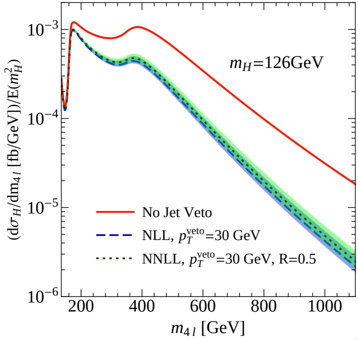
  $\Longrightarrow$ First sensitive to jet algorithm at NNLL: $\log\left(\sqrt{\hat{s}}/p_T^{veto}\right)\log R$

- Normalize result by suppression at m_H. Focus on modification to the shape.

- Large $\hat{s}$ dependent suppression.
- NNLL, NLL results similar.

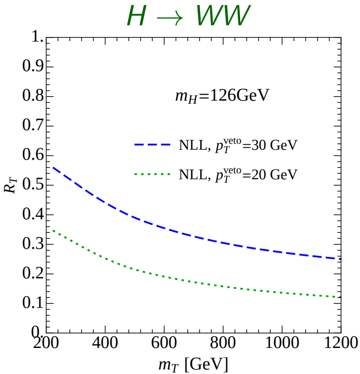
  $\Longrightarrow$ NLL captures dominant modification to shape.

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



Suppression as a Function of M_T

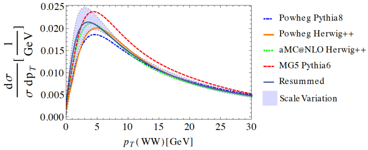
- Can also consider the suppression as a function of the transverse mass, m_T.



- Faster suppression as a function of m_T, since $m_T \leq \sqrt{\hat{s}}$.

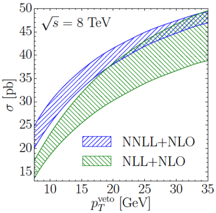
Inclusive $pp \to WW$

- Current interest in p_T, and p_T^{veto} resummation for inclusive $pp \to WW$ cross-section to address anomaly in LHC 8 TeV data.
- Resummation seems to reduce discrepancy between theory and experiment.

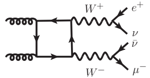


[Meade, Ramani, Zeng 1407.4481]

[Jaiswal, Okui 1407.4537]



- Requires understanding interplay of p_T, and p_T^{veto} resummation, as well as inclusion of contributions from gg initial state.

$\sigma_{WW} \supset \left| \right.$  $\left. \right|^2$