Resummation Effects in Vector-Boson and Higgs Associated Production

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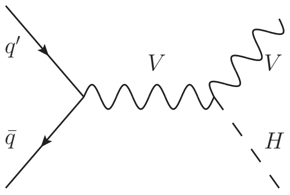
Introduction

- Higgs-like particle is discovered near 125 GeV
- Associated production with a vector boson.
    - Tevatron excesses.
    - Boosted Higgs search for $H \to b\bar{b}$ channel at the LHC

      Butterworth *et al*, PRL 100, 242001 (2008)
    - Probe the *VVH* coupling.



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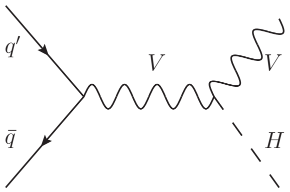

- Rate for *VH* production known up to NNLO Brein, Djouadi, Harlander, PLB579, 149 (2004)
  Brein *et al*, EPJ C72, 1868 (2012)
- Infrared finite results occur due to cancellation of real and virtual soft divergences.
- At edges of phase space, large logs spoil perturbative convergence.
- Large logs should be resummed for sensitive observables.

Introduction

- Near partonic threshold ($z = M^2/\hat{s} \sim 1$): $\alpha_s^n \dfrac{\ln^{2n-1}(1-z)}{1-z}$
- At low transverse momentum ($p_T/M \ll 1$): $\alpha_s^n \ln^{2n-1}\left(\dfrac{M^2}{p_T^2}\right)$
- Techniques for resumming both types of logs are well-known.
- Fixed order and resummed cross sections can be consistently matched at intermediate values.

VH Threshold Resummation

- Generalize the SCET result for Drell-Yan Becher, Neubert, Xu, JHEP 0807, 030 (2008).
- First, a differential cross section can be written as

$$\frac{1}{\tau\sigma_0}\frac{d\sigma}{dM_{VH}^2} = \int_\tau^1 \frac{dz}{z} C(z, M_{VH}, \mu_f)\mathcal{L}\left(\frac{\tau}{z}, \mu_f\right),$$

  - $C(z, M_{VH}, \mu_f) = \delta(1-z) + \mathcal{O}(\alpha_s)$
  - $\tau = M_{VH}^2/s$

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- Near threshold, factorization into hard, $\mathcal{H}$, and soft, $\mathcal{S}$, functions ($z \to 1$):

$$C(z, M_{VH}, \mu_f) = \mathcal{H}(M_{VH}, \mu_f)\mathcal{S}(M_{VH}(1-z), \mu_f)$$

- $\mathcal{H}$ and $\mathcal{S}$ obtained from running the SCET Wilson coefficients from the hard scale, $\mu_h \sim M_{VH}$ down to a soft scale $\mu_s \sim M_{VH}(1-\tau)$

Scale Choice

- Choose soft scale to minimize effects of higher order corrections
  - $\mu_s^I = \dfrac{M_{VH}(1-\tau)}{2\sqrt{1+100\tau}}$ chosen to minimize 1-loop correction to soft piece
  - $\mu_s^{II} = \dfrac{M_{VH}(1-\tau)}{0.9+12\tau}$ chosen when 1-loop correction drops below 10%

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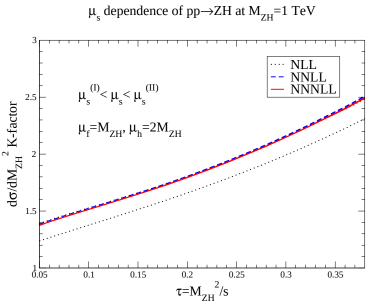
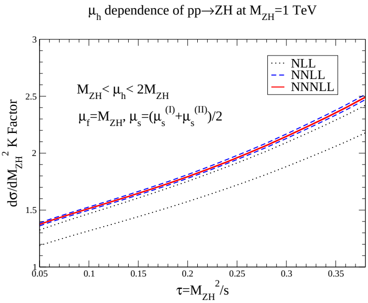
- Analyze scale variation via K-factor:

$$\frac{d\sigma}{dM_{VH}^2} \equiv K \frac{d\sigma}{dM_{VH}^2}\bigg|_{\mathrm{LO}}$$

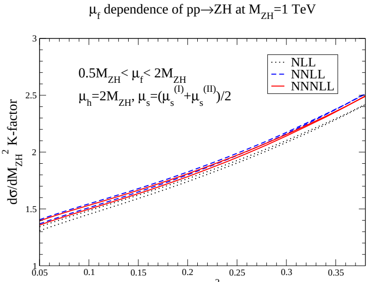
  - $d\sigma/dM_{VH}^2$ is a higher order QCD distribution

Scale dependence





- $d\sigma/dM_{VH}^2$ chosen to be threshold resummed cross section.
- All cross sections evaluated using MSTW2008 NNLO pdfs



Matched Cross sections

- Previous cross sections only included threshold logs.
- For total cross section need to consistently match between threshold and fixed order results:

$$\left[\frac{d\sigma}{dM_{VH}^2}\right]_{matched} = \left[\frac{d\sigma}{dM_{VH}^2}\right]_{threshold\ resum} - \left[\frac{d\sigma}{dM_{VH}^2}\right]_{threshold\ f.o.} + \left[\frac{d\sigma}{dM_{VH}^2}\right]_{f.o.} .$$

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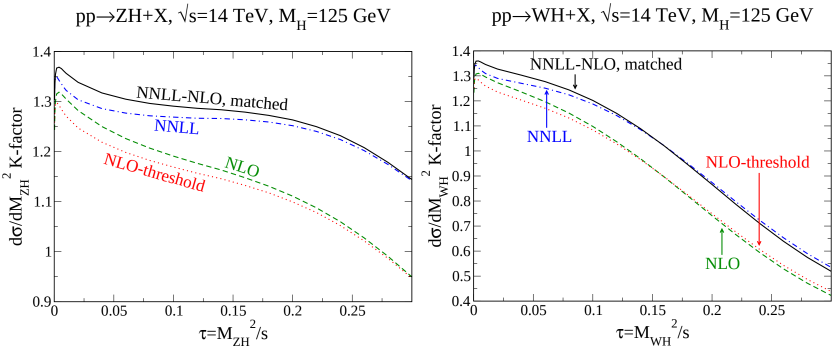
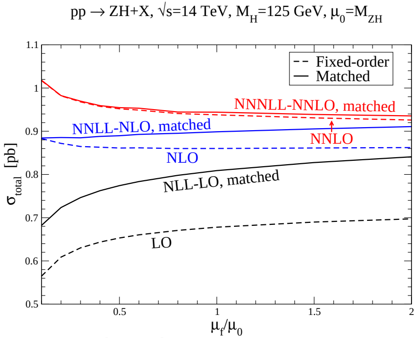
- $\left[\frac{d\sigma}{dM_{VH}^2}\right]_{threshold\ f.o.}$ is the leading singularity of the fixed order result.

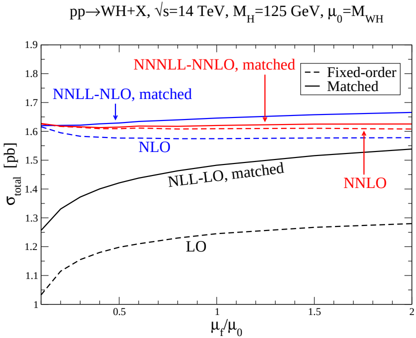
Invariant Mass Distribution



- K-factor evaluated with LO pdfs for LO distibution and NLO pdfs for all others.

14 TeV Cross Sections





- NNNLL has little effect.
- NNLL increases cross section $\sim 7\%$ for ZH and $\sim 3\%$ for WH
- Including threshold logs does not introduce added uncertainty.

- $\mu_s = \frac{1}{2}(\mu_s^I + \mu_s^{II})$
- $\mu_h = 2M_{VH}$
- MSTW2008 68% CL
- Use VH@NNLO for fixed order NNLO result

Brein, Djouadi, Harlander, PLB579, 149 (2004)

Transverse Momentum Resummation

- Apply impact parameter resummation to partonic cross section:
  CSS, Nucl.Phys. B250, 199 (1985); Bozzi *et al*, Nucl.Phys. B737, 73 (2006)

$$\frac{d\hat{\sigma}_{VH}}{dM_{VH}^2 dp_{T,VH}^2} = \frac{d\hat{\sigma}_{VH}^{resum}}{dM_{VH}^2 dp_{T,VH}^2} + \frac{d\hat{\sigma}_{VH}^{finite}}{dM_{VH}^2 dp_{T,VH}^2}$$

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- Resummed piece:

$$M_{VH}^2 \frac{d\hat{\sigma}_{VH}^{resum}}{dM_{VH}^2 dp_{T,VH}^2} = \frac{M_{VH}^2}{\hat{s}} \int_0^\infty db \frac{b}{2} J_0(bp_{T,VH}) W^{VH}(b, M_{VH}, \hat{s}, \mu_r, \mu_f)$$

- $$W_N^{VH}(b, M_{VH}, \mu_r, \mu_f) = H_N^{VH}\left(M_{VH}, \alpha_s(\mu_r), \frac{M_{VH}}{\mu_r}, \frac{M_{VH}}{\mu_f}, \frac{M_{VH}}{Q}\right) \times \exp\left\{G_N\left(\alpha_s(\mu_r), L, \frac{M_{VH}}{\mu_r}, \frac{M_{VH}}{Q}\right)\right\}$$
  - Factorizes into hard, H_N, and soft, G_N, pieces
  - $L = \ln(Q^2 b^2 / b_0^2)$
  - Q is so-called resummation scale.

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  - $H_N^{VH} = \sigma_0(\alpha_s, M_{VH})\left\{1 + \frac{\alpha_s}{\pi} H_N^{VH(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 H_N^{VH(2)} + \cdots\right\}$
  - $G_N = L g_N^1(\alpha_s L) + g_N^2(\alpha_s L) + \left(\frac{\alpha_s}{\pi}\right) g_N^3(\alpha_s L) + \cdots$

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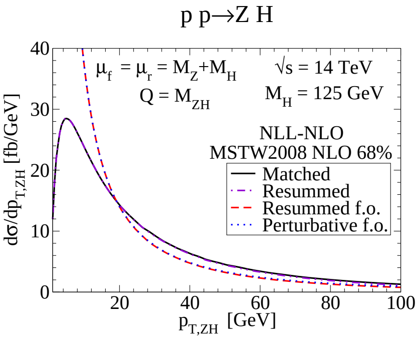
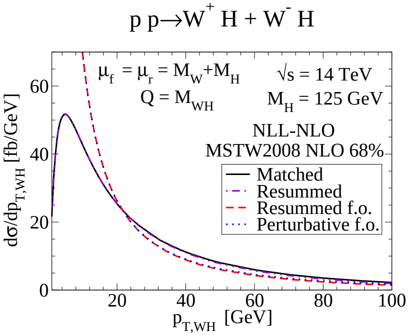
- Finite piece calculated at fixed order:

$$\left[\frac{d\hat{\sigma}_{VH}^{finite}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o} = \left[\frac{d\hat{\sigma}_{VH}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o} - \left[\frac{d\hat{\sigma}_{VH}^{resum}}{dM_{VH}^2 dp_{T,VH}^2}\right]_{f.o}$$

- High and low scale p_T successfully matched

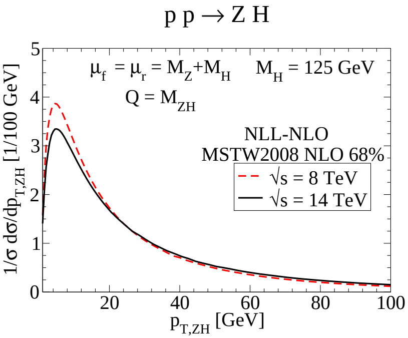
Transverse Momentum Distribution

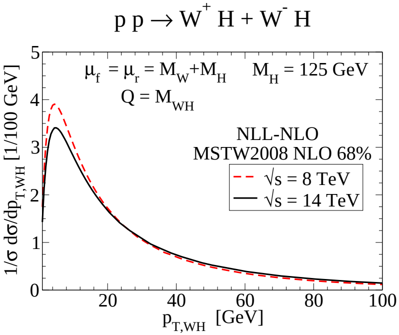




- As expected, perturbative expansions blows up at $p_T \to 0$

Normalized Transverse Momentum Distribution





Jet Cuts

- Jet vetoes can be important for eliminating background.
- Vetoing jets with a minimum p_T may be approximated by placing an upper limit on $p_{T,VH}$
- As shown, the perturbative calculation breaks down in this regime and the soft-gluon resummation is needed.
- There has been much recent work on the systematic resummation of the large logs associated with jet vetoes. Berger *et al*, JHEP 1104, 092 (2011)
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  Tackmann, Walsh, Zuberi, PRD 86, 053011 (2012)

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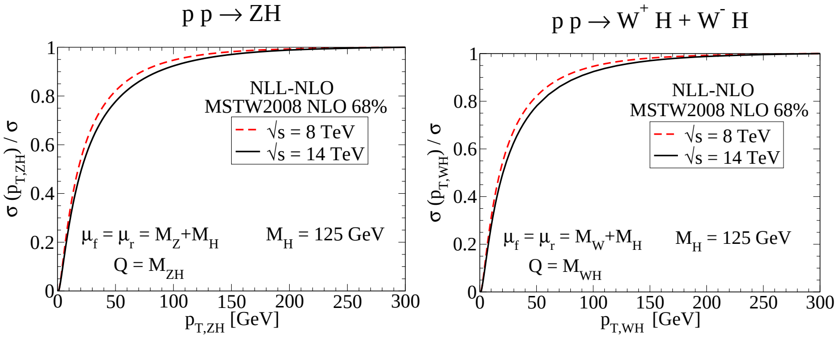
- To measure the approximate effect of the jet vetos define:

$$\sigma(p_{T,VH}) = \int_0^{p_{T,VH}} dq_{T,VH} \frac{d\sigma}{dq_{T,VH}}$$

Transverse Momentum Cut



$1-\dfrac{\sigma(p_{T,VH})}{\sigma}$	8 TeV	14 TeV
$p_{T,VH} < 20$ GeV	$\sim 45\%$	$\sim 50\%$
$p_{T,VH} < 30$ GeV	$\sim 33\%$	$\sim 37\%$

Conclusions

- Now that a Higgs-like particle is discovered, it is imperative to study its properties in detail.
- VH production is one of the most important production mechanisms.
  - Channel through which Tevatron observed its excess.
  - In the boosted regime, can detect $H \to b\bar{b}$ at LHC.
  - Probes the VVH coupling.

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- Performed a detailed numerical analysis of *VH* production at the LHC.
- NNLL threshold resummed result increases fixed-order NLO cross section by $\sim 7\%$ for *ZH* and $\sim 3\%$ for *WH*
- NNNLL threshold resummation has little effect on the NNLO rate, demonstrating excellent convergence of the perturbative series.

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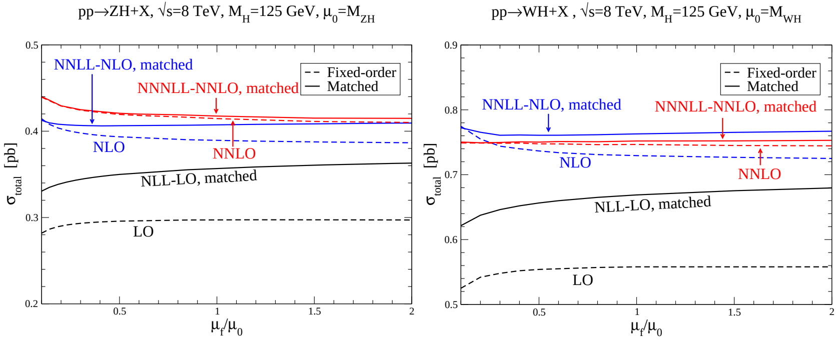
- Performed the transverse momentum resummation of the *VH* system.
- Spectrum slightly harder at 14 TeV than at 8 TeV.
- Calculated the effects on the NLO cross sections of placing a cut on the p_T of the VH system. Expect such a cut to approximate a jet veto.
- Found p_T cut decreased NLO cross section by $33\% - 50\%$

EXTRA SLIDES

8 TeV Cross Sections



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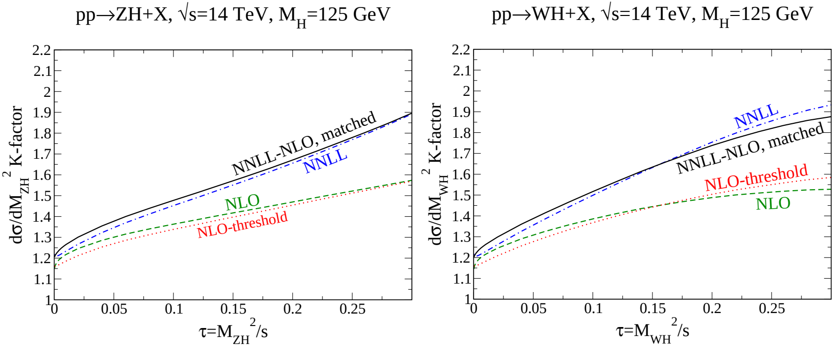

- K-factor evaluated using NLO pdfs for all distributions.