Partial N³LL + NNLO resummation for W^+W^- production under a jet veto

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Talk at LoopFest XV, University at Buffalo, based on arXiv:1606.01034, S. Dawson, P. Jaiswal, Ye Li, H. Ramani, MZ

1 Introduction

- 2 NNLO diboson production in Sherpa
- 3 Jet veto resummation using SCET

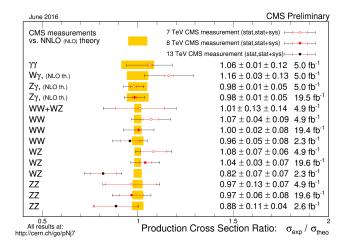
4 Results and comparison with experiment

Section 1

Introduction

- Many diboson final states (*WW*, *WZ*, *ZZ*...) measured by ATLAS and CMS.
- Important tests of SM; constrains anomalous triple and quartic gauge couplings; background to Higgs search.
- For W^+W^- , jet veto used to reduce top pair background large logarithms $\sim \log(m_{WW}/p_T^{\text{veto}})$. Average $\langle \log m_{WW} \rangle \sim \log 200$ GeV. Need resummation

CMS diboson summary

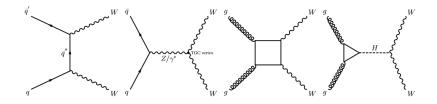


ATLAS diboson summary

$\begin{array}{c} WZ \\ -WZ \rightarrow f v (t) \\ ZZ \\ -ZZ \rightarrow 4t, (tot.) \\ -ZZ \rightarrow 4t \\ -ZZ$	6	∫£ dt [fb ^{−1}]	Reference	
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- ZZ-44 - Z	stat ⊕ syst	3.2	PRL 116, 101801 (2016)	
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QCD corrections for W^+W^- production

Contributions: $q\bar{q} \rightarrow W^+W^-$, loop-induced $gg \rightarrow W^+W^-$, and strongly suppressed Higgs inteference.



[ATLAS-CONF-2014-033]

- $q\bar{q} \rightarrow W^+W^-$ known to NNLO. [Gehrmann, Grazzini, Kallweit, Maierhofer, Manteuffel, Pozzorini, Rathlev, Tancredi '14]
- $gg \to W^+W^-$ known to NLO, formally $\mathcal{O}(\alpha_s^3)$. [Caola, Melnikov, Rontsch, Tancredi '15]

QCD corrections for W^+W^- production

- *p_T* resummation performed up to NNLL + NNLO. [Grazzini, Kallweit, Rathlev, Wiesemann '15]
- Jet veto resummation performed beyond NNLL + NNLO in our work.
- $\blacksquare \sim 20\%$ excess reported by LHC circa 2014. Both NNLO and resummation dramatically improved experiment-theory agreement.
- For example, CMS 8 TeV W^+W^- analysis reweights parton shower events against resummed p_T spectrum, before comparing with NNLO.

Section 2

NNLO diboson production in Sherpa

- Fully differential W⁺W⁻ production in 4FNS. 2-loop matrix elements from qqvvamp. [Gehrmann, von Manteuffel, Tancredi '15, see also Caola, Henn, Melnikov, Smirnov, Smirnov '15]
- 1-loop matrix elements from OpenLoops with customized n_f = 4 library, courtesy of Stefano Pozzorini and Philipp Maierhofer.
- Use *q*_T subtraction [Catani, Cieri, Ferrera, de Florian, Grazzini '09, Catani, Grazzini '07] in the alternative scheme of SCET factorization [Becher, Neubert '10], using 2-loop ingredients from [Gehrmann, Luebbert, Yang '14].

Sherpa implementation of NNLO diboson production

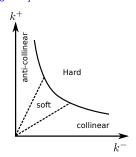
- Below q_T^{cut}: Born rescaled by a customized K factor. Above q_T^{cut}: NLO WW + j, Catani-Seymour.
- 13 TeV total cross section at $\mu = m_W$: (118.4 ± 0.4) pb with $q_T^{\text{cut}} = m_{WW}/200$, 46M points, (118.8 ± 0.8) pb with $q_T^{\text{cut}} = m_{WW}/2000$, 342M points.
- Majority of points and computer time spent on double-real.
- Good cutoff independence, agreeing with [Gehrmann, Grazzini, Kallweit, Maierhofer, Manteuffel, Pozzorini, Rathlev, Tancredi '14].

Section 3

Jet veto resummation using SCET

Jet veto factorization and resummation

■ When p_T^{veto} ≪ m_{WW}, the cross section factorizes into the hard function, soft function, and two beam (collinear) functions. [Stewart, Tackmann, Waalewijn '09; Tackmann, Walsh, Zuberi '12, Becher Neubert '12; Banfi, Monni, Salam, Zanderighi '12]



- We use the language of SCET rapidity RG group [Chin, Jain, Neill, Rothstein, '11, '12], but adopt analytic regulators [Becher, Neubert '12].
- Factorization likely violated $\geq N^4 LL$. [Gaunt '14, MZ '15, Stewart, Rothstein '16]

Jet veto factorization and resummation (cont.)

Factorization formula

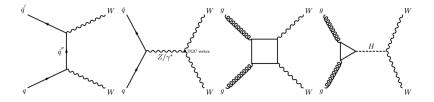
$$\frac{d\sigma}{dm_{WW} dy d\cos\theta} = \sum_{i,j=q,\overline{q},g} \mathcal{H}_{ij}(m_{WW}, \mu_f, \mu_h, \cos\theta) \\
\times \mathcal{B}_i(\xi, p_T^{\text{veto}}, \mu_f, \nu_B, R) \mathcal{B}_j(\overline{\xi}, p_T^{\text{veto}}, \mu_f, \overline{\nu}_B, R) \\
\times \left(\frac{\nu_S \overline{\nu}_S}{\nu_B \overline{\nu}_B}\right)^{g(\mu_f)} \mathcal{S}(p_T^{\text{veto}}, \mu_f, \nu_S, \overline{\nu}_S, R),$$

• Central scales $\nu_B = \bar{\nu}_B = m_{WW}$, $\nu_s = \bar{\nu}_s = \mu_f = p_T^{\text{veto}}$, the bracket term becomes the original **collinear anomaly** exponent [Becher, Neubert '12].

$$\left[\frac{\mu_f^2}{m_{WW}^2}\right]^{g(\mu_f)}$$

• Non-central scales, 1/2 < r < 2, give scale uncertainties,

$$\left[r\frac{\mu_f^2}{m_{WW}^2}\right]^{g(\mu_f)}\left[r^{-g(\mu_f)}\mathcal{B}_i(\mu_f)\mathcal{B}_j(\mu_f)\right]_{\mathcal{O}(\alpha_s^n)}$$



[ATLAS-CONF-2014-033]

We resum $q\bar{q}$ initiated hard scattering to partial N³LL + NNLO, and resum the sub-dominant *gg* initiated hard scattering to NLL + LO.

Log order convention

N^kLL includes
$$\alpha_s^m \log \left(\frac{m_{WW}}{p_T^{\text{veto}}}\right)^{2m-2k+1}$$
. N^kLL' ~ N^(k+1/2)LL includes $\alpha_s^m \log \left(\frac{m_{WW}}{p_T^{\text{veto}}}\right)^{2m-2k}$, equivalent to N^kLL in non-SCET literature.

- Partial N³LL ingredients:
 - (1) 2-loop hard function,
 - (2) Approx. (log terms) 2-loop beam functions,

(3) Pade approx. 4-loop cusp anomalous dimension, 3-loop non-cusp anomalous dimension.

(4) Approx. (log terms) 3-loop collinear anomaly term d_3 , extracted from [Dasgupta, Dreyer, Salam Soyez '14, Banfi, Caola, Dreyer, Monni, Salam, Zanderighi '15].

$$d_3 \approx -64 \log^2 R(1.803136 C_A^2 - 0.589237 N_f C_A + 0.36982 C_F N_f - 0.05893 N_f^2)$$

Two-loop hard function for $q \bar{q} ightarrow W^+ W^-$

 \blacksquare The $\overline{\rm MS}$ UV-renormalized 2-loop $q \bar{q} \to W^+ W^-$ amplitude is

$$\Omega(\epsilon) = \Omega^{(0)} + \left(rac{lpha_s}{2\pi}
ight) \Omega^{(1)} + \left(rac{lpha_s}{2\pi}
ight)^2 \Omega^{(2)}$$

 In qqvvamp, Ω^{finite} obtained from IR counter-terms in the q_T scheme of Grazzini et al.
 SCET hard matching coefficient obtained using pure-pole IR counter-terms.

Conversion formula

$$\mathcal{H}^{\mathrm{SCET}} = \left| \Omega^{\mathrm{finite}} \right|^2 \left[1 + \left(rac{lpha_s}{2\pi}
ight) \tilde{l}_1(\epsilon) + \left(rac{lpha_s}{2\pi}
ight)^2 \tilde{l}_2(\epsilon)
ight],$$

where $\tilde{l}_1(\epsilon) = \frac{\pi^2 C_F}{6}$, and $\tilde{l}_2(\epsilon)$ can be found in our paper.

- The beam function is describes the "probability" of collinear emission not producing an identified jet.
- Equal to PDFs ϕ_i at LO. At higher orders, from convoluting PDFs with kernels,

$$\mathcal{B}_i(\xi, \boldsymbol{p}_T^{\text{veto}}, \mu, R) = \int_{\xi}^1 \frac{dz}{z} \sum_k \boldsymbol{I}_{i \leftarrow k}(z, \boldsymbol{p}_T^{\text{veto}}, \mu, R) \phi_k\left(\frac{\xi}{z}, \mu\right).$$

- One-loop kernel known. [Becher, Neubert '12, Becher, Neubert, Wilhelm '11]
- We obtained two-loop log terms ~ (p_T^{veto}/µ)^m from RG running. Log terms in a different regulator known in [Li, Liu '14].

Example: same-flavor quark to quark kernel

$$\begin{split} \hat{l}_{qq}^{(2)} &= \frac{\left(\Gamma_{0}\right)^{2}}{2} \left(\frac{L_{\perp}}{2}\right)^{4} + \left[(d_{1} - \frac{4}{3}\beta_{0} + 2\gamma_{0})\delta(1 - z)\mathcal{P}_{qq}^{(1)}(z) \right] \Gamma_{0} \left(\frac{L_{\perp}}{2}\right)^{3} \\ &+ \left\{ \left[\frac{d_{1}}{2} (d_{1} + 4\gamma_{0}) - 2\beta_{0} (d_{1} + \gamma_{0}) + 2\gamma_{0}^{2} - \Gamma_{1} \right] \right. \\ &\times \delta(1 - z) - \Gamma_{0} \mathcal{R}_{qq}^{(1)}(z) + (d_{1} - \beta_{0} + 2\gamma_{0})\mathcal{P}_{qq}^{(1)}(z) \\ &+ \frac{\mathcal{P}_{qq}^{(1)}(z) \otimes \mathcal{P}_{qq}^{(1)}(z)}{2} + \frac{\mathcal{P}_{qg}^{(1)}(z) \otimes \mathcal{P}_{gq}^{(1)}(z)}{2} \right\} \left(\frac{L_{\perp}}{2}\right)^{2} \\ &+ \dots \\ &\text{where } L_{\perp} = 2 \log \left(\frac{\mu}{p_{T}^{\text{veto}}}\right). \end{split}$$

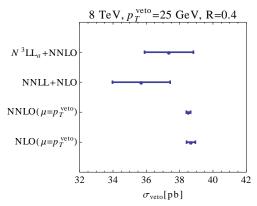
Finite log R terms not included. (below 1% effect). R-dependence comes from d_2 , d_3 , and matching.

Section 4

Results and comparison with experiment

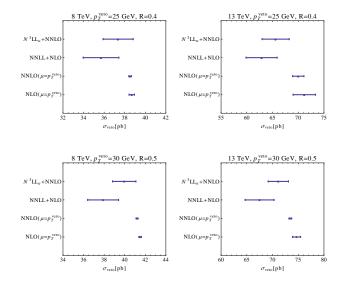
Results: 8 TeV, ATLAS jet veto

• Loop-induced gg not included. Resummed cross section smaller than fixed-order at $\mu = p_T^{\text{veto}} = 25 \text{ GeV}$ (also for $\mu = m_W$). N³LL_a+NNLO higher than NNLL+NLO, with reduced scale uncertainties.



 In qualitative agreement with the estimation based on p_T resummation. [Grazzini, Kallweit, Rathlev, Wiesemann '15]

All results: ATLAS and CMS, 8 TeV and 13 TeV



 Fixed-order results show accidental cancellation, unrealistic small uncertainty, as also happens to Higgs under jet veto. [Becher, Neubert '12]

- Sub-dominant loop-induced gg contribution is resummed to NLL+LO, with π^2 resummation [Ahrens, Becher, Neubert, Yang '08] to simulate the large K factor for LO hard function.
- For 8 TeV, under $p_T^{\text{veto}} = 30$ GeV, R = 0.5: (0.71 ± 0.25) pb, while the total cross section is 1.5 pb at $\mu = m_W$.

 \sim 50% enhancement from π^2 but even larger decrease from jet veto resummation.

• Total, $q\bar{q}$ and gg: (40.7 \pm 1.2) pb.

CMS unfolded, jet veto cut only: 44.0 \pm 0.7(stat) \pm 2.5(exp) \pm 1.4(theo) \pm 1.1 (lumi). [CMS-SMP-14-016]

- We performed partial N³LL + NNLO resummation for W^+W^- production under a jet veto, as used in ATLAS and CMS analyses.
- Small gg loop-induced contribution resummed to NLL+LO.
- Results in good agreement with experimental data.
- NNLO diboson implemented in Sherpa. Future possibilities include other diboson states, decays, and matching to NNLO shower. [Hoeche, Li, Prestel '14]

Thank you!