Partial N^{3}LL + NNLO resummation for W^+W^- production under a jet veto

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based on arXiv:1606.01034, S. Dawson, P. Jaiswal, Ye Li, H. Ramani, MZ

Outline

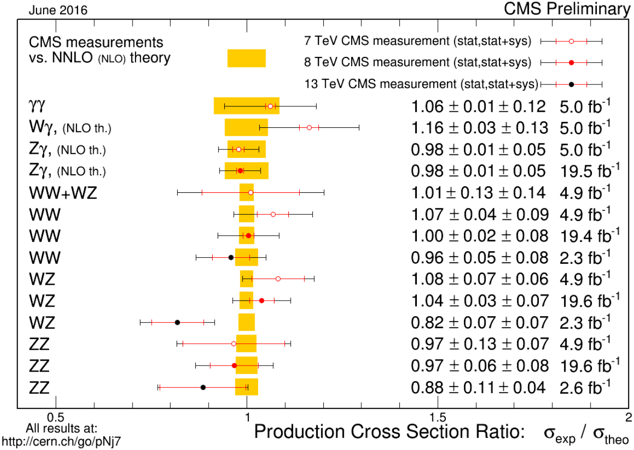
Section 1

Introduction

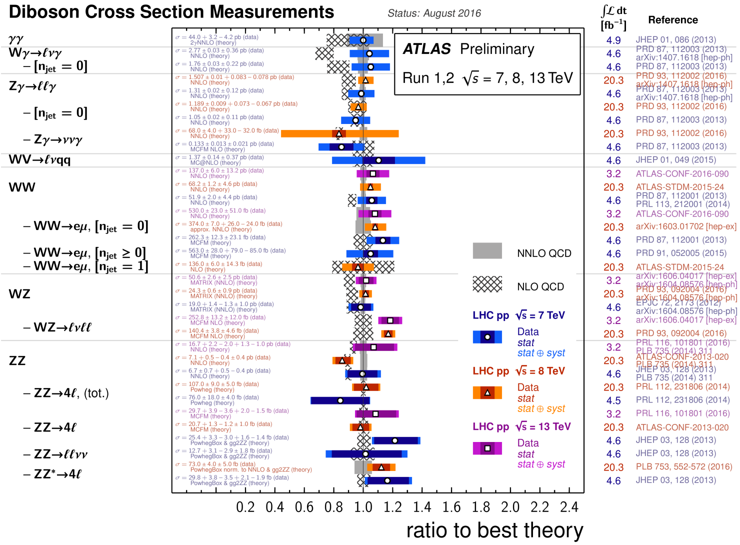
Diboson production at the LHC

- 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 $\sim \log(m_{WW}/p_T^{\rm veto})$. Average $\langle \log m_{WW} \rangle \sim \log 200$ GeV. Need resummation

CMS diboson summary

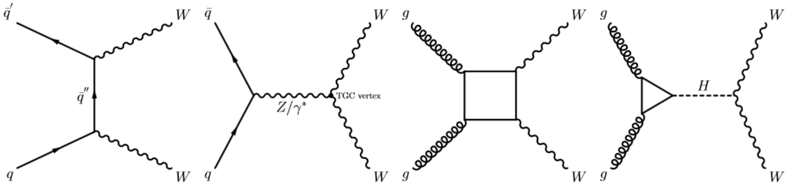


ATLAS diboson summary



QCD corrections for W^+W^- production

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



[ATLAS-CONF-2014-033]

- $q\bar{q} \to W^+W^-$ 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.

- $\sim$ 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

Sherpa implementation of NNLO diboson production

- 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

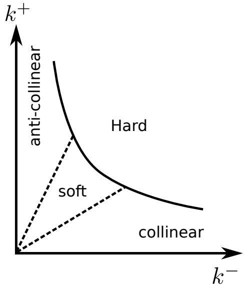
- Below q_T^{cut}: Born rescaled by a customized K factor. Above q_T^{cut}: NLO $WW + j$, Catani-Seymour.
- 13 TeV total cross section at $\mu = m_W$:
  (118.4 ± 0.4) pb with $q_T^{\mathrm{cut}} = m_{WW}/200$, 46M points,
  (118.8 ± 0.8) pb with $q_T^{\mathrm{cut}} = m_{WW}/2000$, 342M points.
- Majority 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 $p_T^{\rm veto} \ll m_{WW}$, 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

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

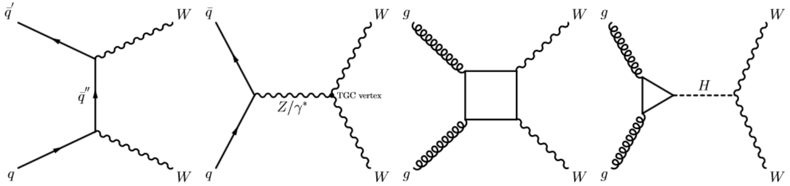
- Central scales $\nu_B = \bar{\nu}_B = m_{WW}$, $\nu_s = \bar{\nu}_s = \mu_f = p_T^{\rm veto}$, the bracket term becomes the original **collinear anomaly** exponent [Becher, Neubert '12].

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

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

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

Resummation order



[ATLAS-CONF-2014-033]

We resum $q\bar{q}$ initiated hard scattering to partial N^{3}LL + NNLO, and resum the sub-dominant gg initiated hard scattering to NLL + LO.

Log order convention

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

- Partial N^{3}LL 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 $q\bar{q} \to W^+W^-$

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

$$\Omega(\epsilon) = \Omega^{(0)} + \left(\frac{\alpha_s}{2\pi}\right)\Omega^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\Omega^{(2)}$$

- 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

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

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

Approximate two-loop beam function

- 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,

$$\mathcal{B}_i(\xi, p_T^{\mathrm{veto}}, \mu, R) = \int_\xi^1 \frac{dz}{z} \sum_k I_{i\leftarrow k}(z, p_T^{\mathrm{veto}}, \mu, R)\, \phi_k\left(\frac{\xi}{z}, \mu\right).$$

- One-loop kernel known. [Becher, Neubert '12, Becher, Neubert, Wilhelm '11]

- We obtained two-loop log terms $\sim (p_T^{\mathrm{veto}}/\mu)^m$ from RG running. Log terms in a different regulator known in [Li, Liu '14].

Example: same-flavor quark to quark kernel

$$\hat{I}_{qq}^{(2)} = \frac{(\Gamma_0)^2}{2}\left(\frac{L_\perp}{2}\right)^4 + \left[(d_1 - \frac{4}{3}\beta_0 + 2\gamma_0)\delta(1-z)\mathcal{P}_{qq}^{(1)}(z)\right]\Gamma_0\left(\frac{L_\perp}{2}\right)^3$$
$$+ \left\{ \left[\frac{d_1}{2}(d_1 + 4\gamma_0) - 2\beta_0(d_1+\gamma_0) + 2\gamma_0^2 - \Gamma_1\right]\right.$$
$$\times\, \delta(1-z) - \Gamma_0\mathcal{R}_{qq}^{(1)}(z) + (d_1 - \beta_0 + 2\gamma_0)\mathcal{P}_{qq}^{(1)}(z)$$
$$\left. + \frac{\mathcal{P}_{qq}^{(1)}(z)\otimes\mathcal{P}_{qq}^{(1)}(z)}{2} + \frac{\mathcal{P}_{qg}^{(1)}(z)\otimes\mathcal{P}_{gq}^{(1)}(z)}{2}\right\}\left(\frac{L_\perp}{2}\right)^2$$
$$+ \dots$$

where $L_\perp = 2\log\left(\frac{\mu}{p_T^{\mathrm{veto}}}\right)$.

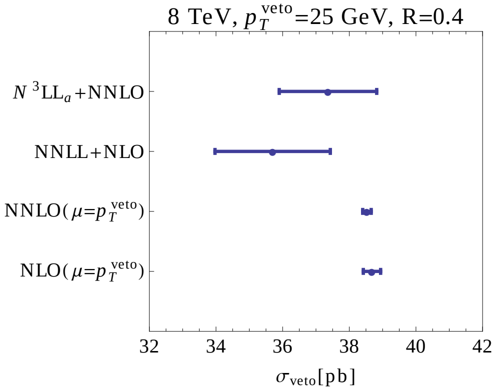
Finite log R terms not included. (below 1% effect). R-dependence comes from d_2, d_3, and matching.

Section 4

Results and comparison with experiment

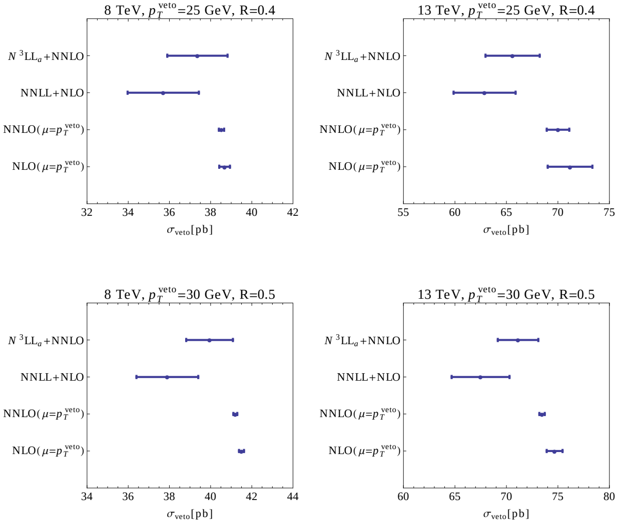
Results: 8 TeV, ATLAS jet veto

- Loop-induced gg not included. Resummed cross section smaller than fixed-order at $\mu = p_T^{\text{veto}} = 25$ GeV (also for $\mu = m_W$). N^{3}LL$_a$+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]

Comparison with CMS

- 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 $p_T^{\rm veto} = 30$ 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 ± 1.2) pb.

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

Conclusion

- We performed partial N^3LL + 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!