Diboson production in NNLO QCD

Dirk Rathlev

based on work with: M. Grazzini, S. Kallweit and A. Torre
Phys.Lett. B731 (2014) 204-207 [arXiv:1309.7000 [hep-ph]]

F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, L. Tancredi, E. Weihs
Phys.Lett. B735 (2014) 311-313 [arXiv:1405.2219 [hep-ph]]

T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, L. Tancredi
Phys.Rev.Lett. 113 (2014) [arXiv:1408.5243 [hep-ph]]

Universität Zürich

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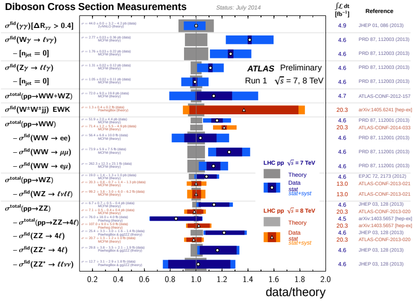
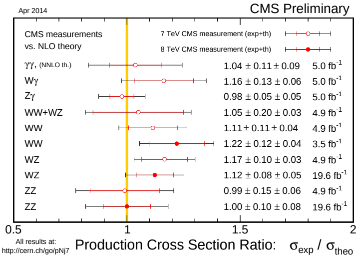
Vector boson pair production

- vector boson pair production $pp \to VV'$ logical next step in the NNLO program
    - important standard model test
    - background for Higgs analyses and BSM searches
    - experimental accuracy is approaching uncertainty of NLO prediction
    - some moderate excesses in the experimental data



[ATLAS collaboration (2014)]



[CMS collaboration (2014)]

Ingredients for $pp \to VV'$

- amplitudes:
  - $pp \to VV' + 2$ partons at tree level
  - $pp \to VV' + 1$ parton at one loop
  - $pp \to VV'$ at two loops $\to$ typically the bottleneck
  - $gg \to VV'$ loop-induced
- tree- and one-loop amplitudes from OpenLoops [Cascioli, Maierhöfer, Pozzorini (2012)]
- two-loop amplitudes now available:
  - $\gamma\gamma$ [Anastasiou, Glover, Tejeda-Yeomans (2002)]
    $\to$ diphoton production at NNLO [Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
  - $V\gamma$ [Matsuura, van der Marck, van Neerven (1989); Gehrmann, Tancredi (2012)]
    $\to$ $Z\gamma$ production at NNLO [Grazzini, Kallweit, DR, Torre (2013)]
  - VV [Gehrmann, von Manteuffel, Tancredi, Weihs (2014)]
    $\to$ on-shell ZZ, WW production at NNLO [F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, DR, L.Tancredi, E. Weihs (2014)]
- numerical cancellation of intermediate IR singularities
  $\to$ use q_T subtraction [Catani, Grazzini (2007)]

q_T subtraction method

- applicable to production of colorless final state F

$$\mathrm{d}\sigma^{\mathrm{F}}_{\mathrm{(N)NLO}} = \mathcal{H}^{\mathrm{F}}_{\mathrm{(N)NLO}} \otimes \mathrm{d}\sigma_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}} - \mathrm{d}\sigma^{\mathrm{CT}}\right]$$

- counterterm $\mathrm{d}\sigma^{\mathrm{CT}} = \Sigma(q_T/Q) \otimes \mathrm{d}\sigma_{\mathrm{LO}}$, cancels $q_T \to 0$ singularity of $\mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}}$
- $\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right) \Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2 \Sigma^{(2)}(q_T/Q) + \dots$
- hard function $\mathcal{H}^{\mathrm{F}}$ contains radiative corrections to Born level subprocess
- $\mathcal{H}^{\mathrm{F}} = \underbrace{1}_{\text{tree level}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{\mathrm{F}(1)}}_{\text{(finite) one-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{\mathrm{F}(2)}}_{\text{(finite) two-loop amplitude}} + \dots$

$W\gamma$: measurement

- $\sim 2\sigma$ excess in ATLAS measurement, but NLO corrections are large ($\sim$ 100%)

	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012

[ATLAS collaboration (2013)]

- could be a NNLO effect

$W\gamma$: Setup and cross sections

- we present results for $pp \to \ell^{\pm}\nu_{\ell}\gamma + X$
- setup close to the ATLAS analysis [ATLAS collaboration (2013)]
  - $p_T^{\gamma} > 15$ GeV, $|\eta^{\gamma}| < 2.37$
  - $p_T^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.47$
  - $p_{T,miss} > 35$ GeV
  - $\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
  - Frixione isolation with $\varepsilon = 0.5$, $R = 0.4$
- **preliminary:** [M. Grazzini, S. Kallweit, DR, A. Torre]

		LO	NLO	NNLO	exp.
W^+	σ [pb]	0.511	1.155	1.361	
	rel. correction		126%	18%	
W^-	σ [pb]	0.395	0.910	1.077	
	rel. correction		130%	18%	
total	σ [pb]	0.906	2.065	2.438	2.770(340)
	rel. correction		128%	18%	

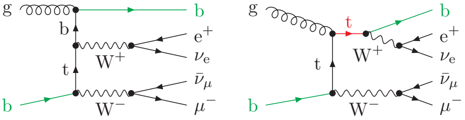
$pp \to W^+W^-$

- WW production one of the most important diboson processes
  - larger cross section than ZZ and WZ
  - final state $\ell^+\ell^-\nu\bar{\nu}$ cannot be fully reconstructed
- persistent $\sim 2\sigma$ excess in ATLAS and CMS measurements
- experimentally challenging due to large top background
- top-subtracted fiducial cross section gets extrapolated back to total W^+W^- cross section

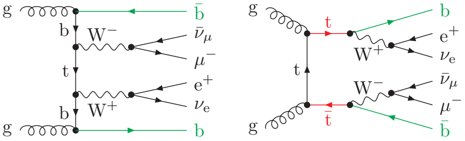
	$\sigma\,(pp \to W^+W^-)$ [pb]	SM NLO [pb]
ATLAS 7 TeV [ATLAS collaboration (2012)]	51.9 ± 4.8	$44.7^{+2.1}_{-1.9}$
CMS 7 TeV [CMS collaboration (2013)]	52.4 ± 5.1	
ATLAS 8 TeV [ATLAS collaboration (2014)]	71.4 ± 5.3	$57.3^{+2.4}_{-1.6}$
CMS 8 TeV [CMS collaboration (2013)]	69.9 ± 7.0	

$pp \to W^+W^-$

- $\sigma\,(pp \to W^+W^-)$ is not well-defined in naive PT
  - at NLO: contribution from $gb \to Wt \to WWb$



  - at NNLO: contribution from $q\overline{q}/gg \to t\overline{t} \to WWb\overline{b}$



  - large "higher-order corrections" corrections (30%/400% at NLO/NNLO)
  - cannot consistently be removed in 5FS, due to collinear singularities

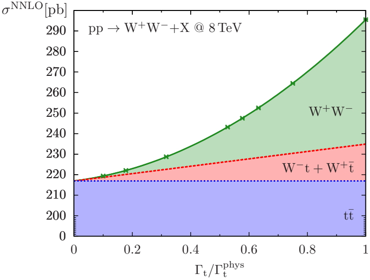
$pp \to W^+W^-$

- WW cross section is well-defined in 4FS (due to massive b's), but how to quantify the inherent uncertainty?
- can exploit different scaling behaviour of genuine WW, single top and top pair production w.r.t. Γ_t

$$\sigma_{\mathrm{WW}} \propto 1, \quad \sigma_{\mathrm{Wt}} \propto \Gamma_t^{-1}, \quad \sigma_{\mathrm{tt}} \propto \Gamma_t^{-2}$$

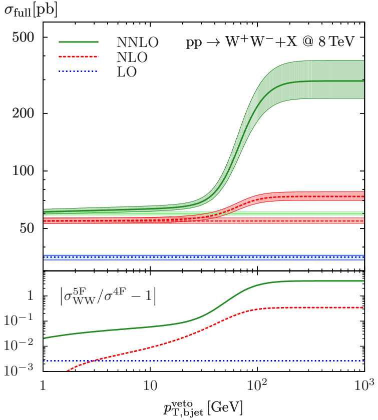
- fit quadratic polynomial to $\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)^2 \sigma_{5FS}\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)$

$$\sigma_{\mathrm{5FS}} = \sigma_{\mathrm{WW}} + \sigma_{\mathrm{Wt}} + \sigma_{\mathrm{tt}}$$



$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

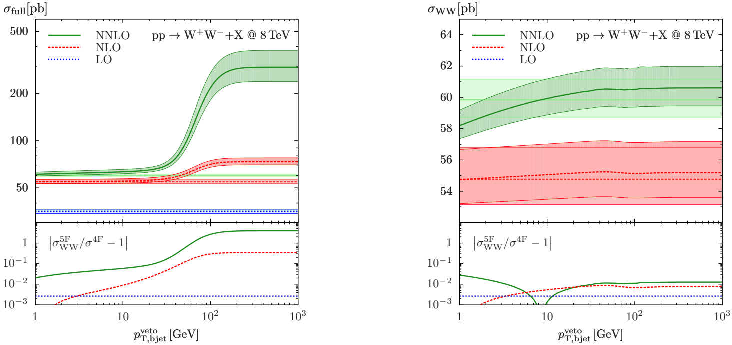
- expect b-jet-veto to suppress the top contamination



- at "typical" $p_{T,\text{bjet}}^{\text{veto}} \sim 30\,\text{GeV}$, about 15% enhancement remains
- $p_{T,\text{bjet}}^{\text{veto}} \to 0$ limit cannot be taken (infrared divergence)

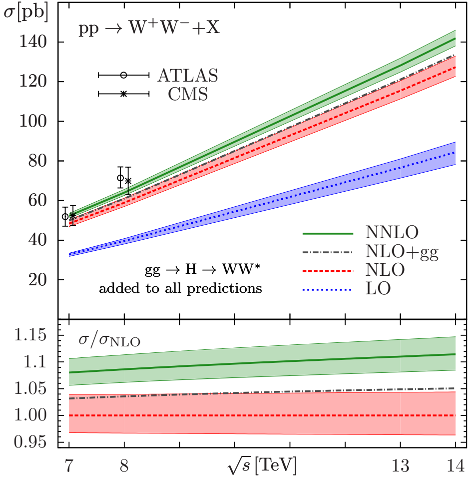
$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

- $\sigma_{\rm WW}$ should not change when applying a b-jet veto if properly defined



- σ_{WW} is stable above $p_{T,bjet}^{veto} \approx 30\,\text{GeV}$, coincides with 4FS result (within $\sim 2\%$)
- logarithmic singularity at small $p_{T,\rm bjet}^{\rm veto}$

$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]



- NNLO corrections range from 9% to 12%
- gg fusion contribution is about 35% of the NNLO correction

Conclusion

- ambitious project to provide NNLO prediction for all diboson production processes
- fully differential NNLO QCD computation of $Z\gamma$ and $W^{\pm}\gamma$ production
  - full decay, spin correlations and off-shell effects included
  - corrections for $W^{\pm}\gamma$ larger than for $Z\gamma$
- inclusive on-shell production of WW at NNLO
  - top contamination can be consistently removed
  - discrepancy with data significantly reduced
- outlook:
  - fully differential ZZ/WW production, including the decay
  - WZ and ZZ, WW including off-shell effects
  - code not ready for publication yet, but we are happy to provide numbers

Backup slides

$Z\gamma$: ATLAS and CMS setup

- ATLAS inspired setup [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$ or $p_T^\gamma > 40\,\text{GeV}$, $|\eta^\gamma| < 2.37$, $p_T^\ell > 25\,\text{GeV}$, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40\,\text{GeV}$
  - $\Delta R(\ell, \gamma) > 0.7$
  - $\Delta R(\ell/\gamma, jet) > 0.3$, where $E_T^{jet} > 30\,\text{GeV}$ and $|\eta^{jet}| < 4.4$, jets clustered using the anti-k_T algorithm with radius $D = 0.4$
  - smooth cone isolation with $\delta_0 = 0.4$ and $\varepsilon = 0.5$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$

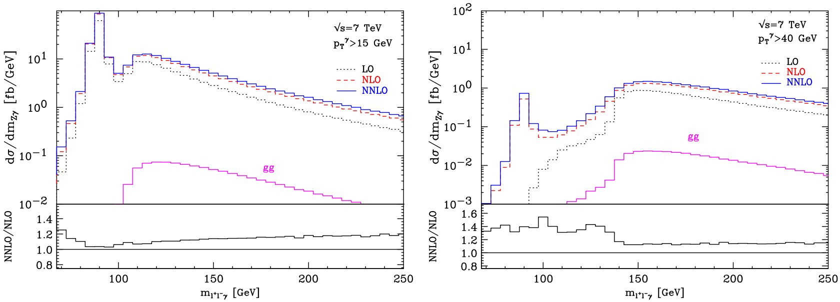
- CMS inspired setup [CMS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$, $|\eta^\gamma| < 2.5$, $p_T^\ell > 20\,\text{GeV}$, $|\eta^\ell| < 2.5$
  - $m_{\ell\ell} > 50\,\text{GeV}$
  - $\Delta R(\ell, \gamma) > 0.7$
  - smooth cone isolation with $\delta_0 = 0.15$ and $\varepsilon = 0.05$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$

$Z\gamma$: Setup and cross sections

- we present results for $pp \to \ell^+\ell^-\gamma + X$ [M. Grazzini, S. Kallweit, DR, A. Torre (2013)]
- setup close to the ATLAS analysis [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15$ GeV or $p_T^\gamma > 40$ GeV, $|\eta^\gamma| < 2.37$
  - $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40$ GeV
  - $\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
  - Frixione isolation with $\varepsilon = 0.5$, $R = 0.4$

		LO	NLO	NNLO	exp.
$p_T^\gamma > 15$ GeV	σ [pb]	0.851(1)	1.226(1)	1.308(3)	1.31(12)
	rel. correction		44%	7%	
$p_T^\gamma > 40$ GeV	σ [fb]	77.45(3)	132.90(8)	153.3(5)	
	rel. correction		72%	16%	
CMS setup	σ [pb]	1.334(1)	1.891(1)	2.021(5)	
[CMS collaboration (2013)]	rel. correction		42%	7%	

$Z\gamma$: Invariant mass distribution



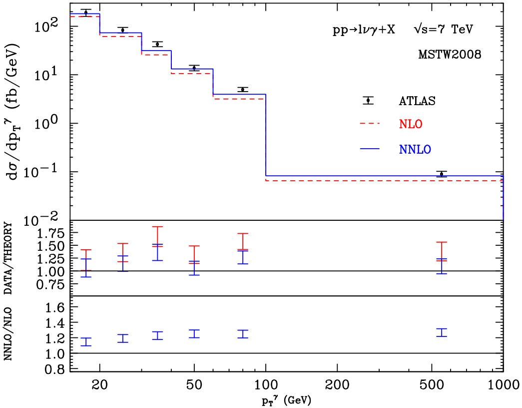
- implicit cuts at LO can increase corrections significantly
- *gg* fusion contribution very small ($\sim$ 8% of the NNLO correction)

$Z\gamma$: Contributions by channel

	$q\overline{q}$	gq	$g\overline{q}$	gg	qq	$\overline{qq}$	total [fb]
LO	851						851
NLO	1255	-6	-23				1226
NNLO	1350	-16	-38	6	6	1	1309

- $q\overline{q}$ the dominant channel at each order and also has the largest corrections
- gq and $g\overline{q}$ have negative weight
- gg is tiny

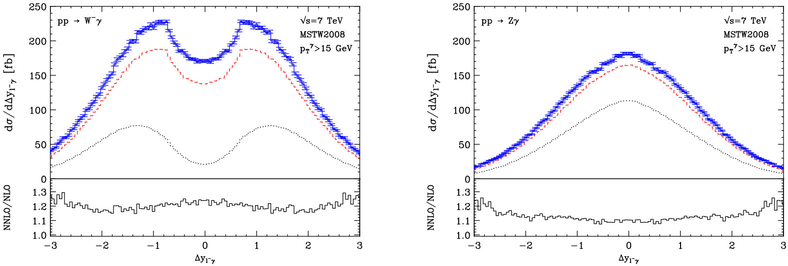
$W\gamma$: Comparison with data



- NNLO effect grows with p_T
- agreement with data improved

$W\gamma$: Origin of the large K factor

- on-shell $q\bar{q} \to W\gamma \Rightarrow$ tree-level amplitude exactly vanishes at $\cos\theta^*_{W\gamma} = \pm\frac{1}{3}$
- gets filled up by real radiation, PDF convolution and FSR
- clearly visible as dip at the LHC after switching off FSR



- corrections do not respect the zero, relative impact is enlarged

Scale uncertainties

- *symmetric* scale variations around $\mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2}$ tiny at NLO due to an accidental cancellation
- follow suggestion by MCFM authors and vary $\mu_R = a\mu_0,\ \mu_F = \mu_0/a,\ a \in [0.5,2]$ [Campbell, Ellis, Williams (2011)]

σ [fb]	LO	NLO	NNLO	$\frac{\text{NNLO}}{\text{NLO}} - 1$
$Z\gamma$	$850.7^{+7\%}_{-9\%}$	$1226.2^{+4\%}_{-5\%}$	$1308^{+1\%}_{-2\%}$	6.7%
$W^+\gamma$	$511.0^{+6\%}_{-7\%}$	$1155.3^{+7\%}_{-7\%}$	$1371^{+5\%}_{-4\%}$	18.7%
$W^-\gamma$	$395.3^{+6\%}_{-8\%}$	$909.9^{+7\%}_{-7\%}$	$1085^{+4\%}_{-4\%}$	19.2%

$pp \to ZZ$

$\sqrt{s}$ [TeV]		LO	NLO	NNLO
7	σ [pb]	$4.167^{+0.7\%}_{-1.6\%}$	$6.044^{+2.8\%}_{-2.2\%}$	$6.735^{+2.9\%}_{-2.3\%}$
	rel. size		45%	11%
8	σ [pb]	$5.060^{+1.6\%}_{-2.7\%}$	$7.369^{+2.8\%}_{-2.3\%}$	$8.284^{+3.0\%}_{-2.3\%}$
	rel. size		46%	12%
13	σ [pb]	$9.887^{+4.9\%}_{-6.1\%}$	$14.51^{+3.0\%}_{-2.4\%}$	$16.91^{+3.2\%}_{-2.4\%}$
	rel. size		47%	17%
14	σ [pb]	$10.91^{+5.4\%}_{-6.7\%}$	$16.01^{+3.0\%}_{-2.4\%}$	$18.77^{+3.2\%}_{-2.4\%}$
	rel. size		47%	17%

- scale uncertainties computed with $1/2M_Z < \mu_R,\, \mu_F < 2M_Z$ with $1/2 < \mu_R/\mu_F < 2$
- scale variations very small at LO, NLO; underestimate size of corrections

$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

$\sqrt{s}$ [TeV]		LO	NLO	NNLO
7	σ [pb]	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$
	rel. size		53%	9%
8	σ [pb]	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$
	rel. size		54%	9%
13	σ [pb]	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$
	rel. size		58%	12%
14	σ [pb]	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$
	rel. size		58%	12%

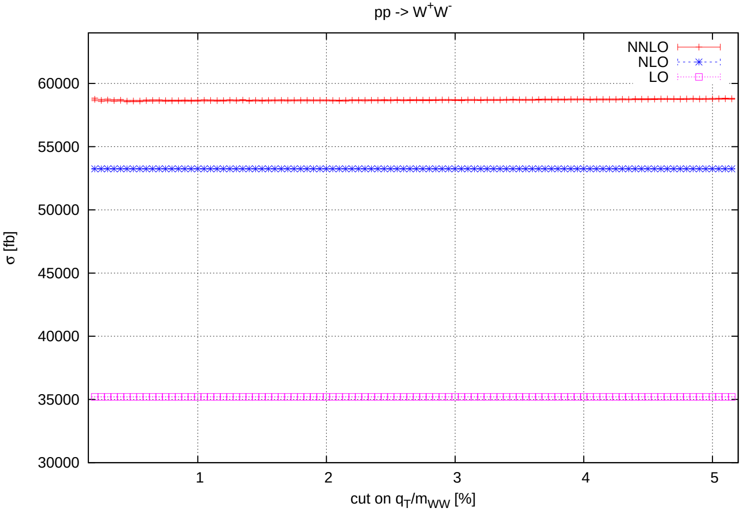
- scale uncertainties computed with $1/2M_W < \mu_R,\ \mu_F < 2M_W$ with $1/2 < \mu_R/\mu_F < 2$
- scale variations very small at LO, NLO; underestimate size of corrections

$pp \to W^+W^-$: current limitations

- limited to on-shell Ws
  - expect $\sim -2\%$ off-shell effects
  - work on off-shell amplitudes is underway, but numerical stability might be an issue [F. Caola, J. Henn, K. Melnikov, A. Smirnov, V. Smirnov (2014)]
- spin correlations not taken into account
  - irrelevant for total cross section
  - useful to implement experimental cuts
  - need helicity amplitudes
    $\to$ might become available soon, but still on-shell
- $gg \to W^+W^-$ contribution only included at LO
  - need two-loop $gg \to W^+W^-$ amplitudes for NLO, not available
  - corrections could be up to $+4\%$ [M. Bonvini, F. Caola, S. Forte, K. Melnikov, G. Ridolfi (2013)]
- NLO EW corrections are negligible

$pp \to W^+W^-$: Stability I

- check independence of phase space regulator (small cut on q_T/Q)



$pp \to W^+W^-$: Stability II

- check independence of phase space regulator (small cut on q_T/Q)