Theory review on diboson production

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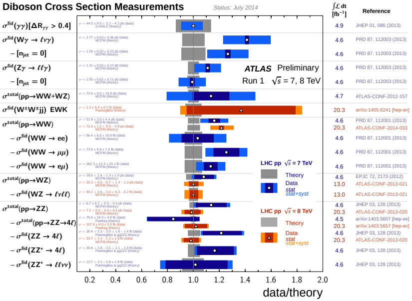
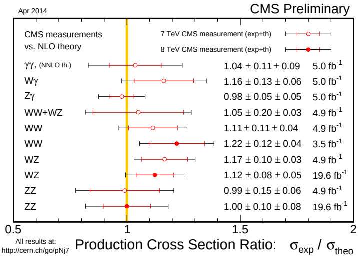
Vector boson pair production

- vector boson pair production $pp \to VV'$ is a crucial part of the LHC physics programme
  - important standard model test, directly probes non-Abelian interactions
  - background for Higgs analyses and BSM searches
  - experimental accuracy is approaching the percent level



[ATLAS collaboration (2014)]



[CMS collaboration (2014)]

QCD corrections: ingredients

- NLO QCD corrections available for all diboson processes, including correlations and off-shell effects, for example in MCFM

  [Campbell, Ellis, Williams (2011)]

- NNLO subtraction well understood, e.g. q_T subtraction [Catani, Grazzini (2007)]
- up to now: bottleneck were the two-loop amplitudes, but now the list is finally complete:
  - $\gamma\gamma$: [Anastasiou, Glover, Tejeda-Yeomans (2002)]
  - $Z\gamma$ and $W\gamma$: [Gehrmann, Tancredi (2012)]
  - VV on-shell: [Gehrmann, von Manteuffel, Tancredi, Weihs (2014)]
  - VV': [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); Gehrmann, von Manteuffel, Tancredi (2015)]
- [Gehrmann, von Manteuffel, Tancredi (2015)] provide a stable and sufficiently fast numerical implementation of the helicity amplitudes
- in the not so far future: pertubative accuracy of all diboson processes at full NNLO in QCD!

QCD corrections: gluon fusion contributions

- for $Z\gamma$, ZZ and W^+W^- there is loop-induced gluon fusion contribution:

$$gg \to VV'$$

- formally starts to contribute at $\mathcal{O}\left(\alpha_S^2\right)$, i.e. at NNLO
- only known to leading order (NLO requires two-loop amplitudes)
- contribution between the $\lesssim 1\%$ ($Z\gamma$) and the 5% level (ZZ and W^+W^-)
- for ZZ and W^+W^- this is the largest source of theoretical uncertainty after inclusion of NNLO corrections
- now the dominant part of the two-loop amplitudes is known

  [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)]
- expect NLO corrections to be available in the near future

Photon isolation I

- relevant for $\gamma\gamma$, $Z\gamma$, $W^{\pm}\gamma$
- two contributions to photon production:
  - direct production in the hard process, e.g. genuine $Z\gamma$ production
  - non-perturbative fragmentation of a hard parton
- in experiments, impose hard cone isolation: $\sum_{\delta<R} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma$
- needs non-perturbative fragmentation contribution for IR finiteness
- smooth cone isolation [Frixione (1998)]: define $\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R)}\right)^n$,

$$\sum_{\delta'<\delta} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma \, \chi(\delta) \quad \text{for all} \quad \delta \leq R$$

- smooth cone isolation eliminates fragmentation contribution completely

Photon isolation II

$$\sum_{\delta' < \delta} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma \left(\frac{1 - \cos(\delta)}{1 - \cos(R)} \right)^n \quad \text{for all} \quad \delta \leq R$$

- significantly simplifies theoretical computations
- difficult to implement experimentally
- mismatch if hard QCD and fragmentation contribution included at different orders $\rightarrow$ unphysical effects [Cieri, de Florian (2014)]
- smooth cone very close to (correct) fragmentation result for tight isolation
- NNLO QCD corrections more important than fragmentation
- Les Houches report: adopt pragmatic approach
  $\rightarrow$ tight isolation, compare with smooth cone predictions

$W\gamma$: measurement

- $\sim 2\sigma$ excess over NLO QCD in ATLAS measurement

	$\sigma^{\text{ext-fid}}$[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)]

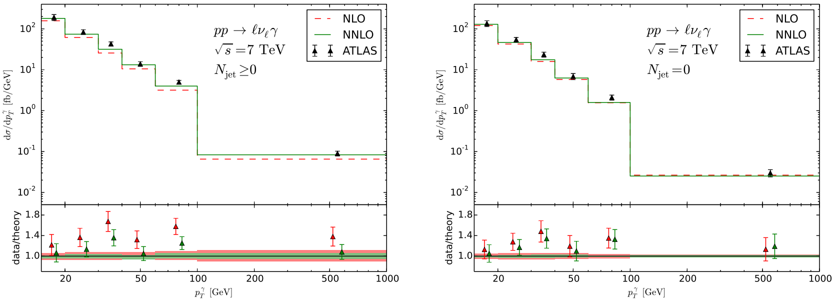
- NLO corrections are large ($\sim 100\%$) $\Rightarrow$ higher order corrections mandatory

$W\gamma$: Setup and cross sections

- results for $pp \to \ell^{\pm}\nu_{\ell}\gamma + X$
- ATLAS cuts [ATLAS collaboration (2013)]
  - $p_T^{\gamma} > 15$ GeV, $|\eta^{\gamma}| < 2.37$
  - $p_T^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.47$
  - $p_{T,\mathrm{miss}} > 35$ GeV
  - $\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
  - Frixione isolation with $\varepsilon = 0.5$, $R = 0.4$
- results: [M. Grazzini, S. Kallweit, DR; 1504.01330]

	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]
$N_{\mathrm{jet}} \geq 0$	$0.8726^{+6.8\%}_{-8.1\%}$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)
$N_{\mathrm{jet}} = 0$		$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)

$W\gamma$: Comparison with data



- agreement with data improved
- relatively hard radiation
- see also findings by MiNLO collaboration [Barzè, Chiesa, Montagna, Nason, Nicrosini, Piccinini, Prosperi (2014)]
- $W\gamma$ is a special case: radiation zero at tree level is broken by real corrections

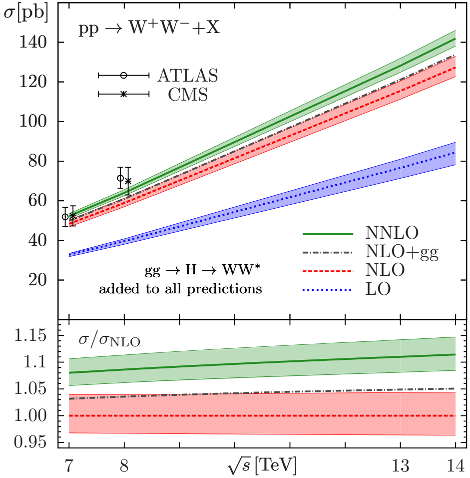
$pp \to W^+W^-$

- WW production one of the most important diboson processes
- $\sim 2\sigma$ excess in ATLAS and CMS measurements over NLO QCD
- experimentally challenging due to large top background
- top background gets suppressed by jet veto
- top-subtracted fiducial cross section gets extrapolated back to total W^+W^- cross section
  $\Rightarrow$ precise modelling of jet veto efficiency needed

	$\sigma\,(pp \to W^+W^-)$ [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	

W^+W^-: the inclusive cross section

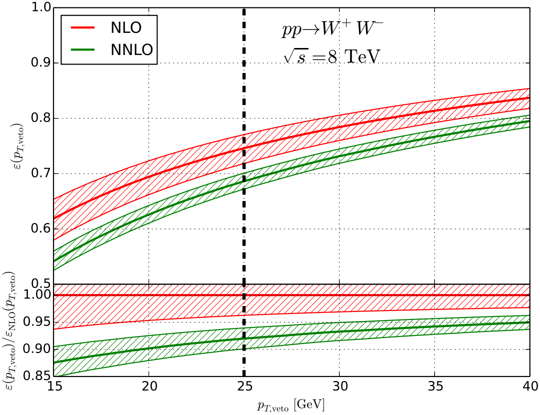
[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi; 1408.5243]



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

W^+W^-: jet-veto effects, NNLO vs. NLO

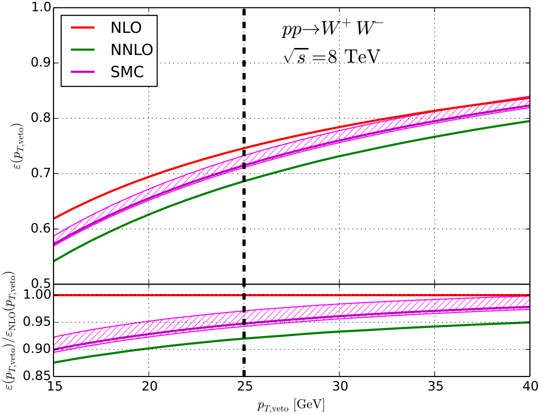
[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- fiducial region is defined with a jet veto, $p_{T,\rm veto} = 25\,\text{GeV}$
- fixed order prediction might be affected by large logs

W^+W^-: jet-veto effects, NLO+PS

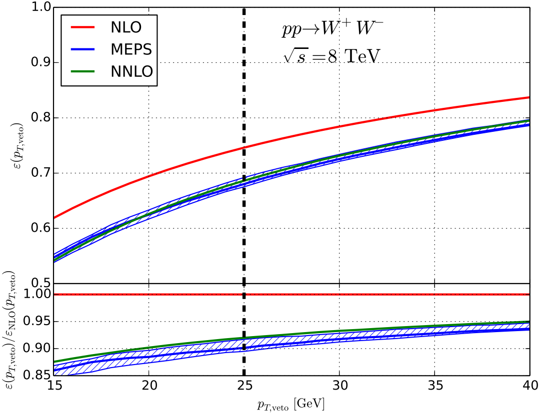
[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- NLO+PS lowers efficiency
- marginally consistent with NNLO

W^+W^-: jet-veto effects, MEPS

[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- first emission with NLO accuracy
- agrees with NNLO
- but missing higher log effects might still be sizeable

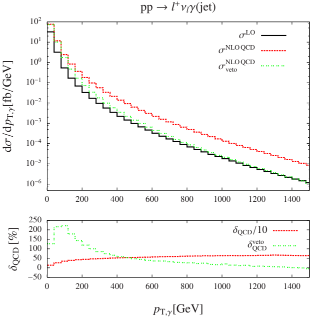
W^+W^-: some remarks

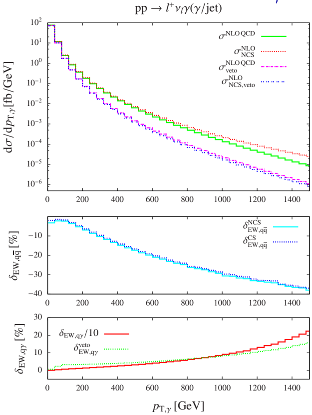
- new CMS measurement: $\sigma_{W^+W^-} = 61.1 \pm 4.8\,\text{pb}$ [CMS collaboration (2015)]
  - prediction reweighted with NNLL p_T^{WW} resummed computation [Meade, Ramani, Zeng (2015)]
  - expect strong correlation between jet veto and p_T^{WW}
  - this should be carefully checked!
  - very good agreement with $\sigma^{\text{NNLO}}_{W^+W^-} = 59.84\,\text{pb}^{+2.2\%}_{-1.9\%}$
- NNLO predictions for the fiducial cross section now feasible
  - how to combine with p_T resummation or parton shower?
- dominant theoretical uncertainty on integrated cross section now from gg contribution
  - $1.6\,\text{pb}$ at LO (8 TeV), possible corrections up to 100% $\rightarrow\sim$ 3% uncertainty on $\sigma^{\text{NNLO}}_{W^+W^-}$
  - expect NLO result soon
- PDF uncertainties and NLO EW on the 1% level

EW corrections

- formally, $\mathcal{O}(\alpha_{EW}) \sim \mathcal{O}(\alpha_S^2)$
  $\Rightarrow$ NLO EW should be as important as NNLO QCD
- in practice: for integrated observables, EW corrections are small
- however, they come with high energy logs of the form $\log E/M_Z$
  $\rightarrow$ expect big effects in high energy tails
- enormous progress in the automation of NLO EW corrections
  - virtual amplitudes: RECOLA [Actis, Denner, Hofer, Scharf, Uccirati (2013)], OpenLoops [Cascioli, Lindert, Maierhöfer, Pozzorini (2014)]
  - automation of subtraction: SHERPA and MUNICH [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr (2014)]
  - MadGraph5_aMC@NLO [Frixione, Hirschi, Pagani, Shao, Zaro (2015)]
- complete computation of NLO EW corrections to all diboson processes (plus jets) in the near future

EW corrections: $W\gamma$





- taken from [Denner, Dittmaier, Hecht, Pasold (2014); 1412.7421]
- EW corrections partially cancel, but important already around $p_T^\gamma \sim 250\,\text{GeV}$
- without jet veto, QCD corrections much larger, but flattening
- jet veto suppresses QCD corrections, EW mostly unaffected

Summary

- significant progress on the NNLO QCD corrections to diboson production
  - photon isolation theory $\leftrightarrow$ experiment
  - $\gamma\gamma$, $Z\gamma$ and $W^{\pm}\gamma$ completed
  - on-shell ZZ and W^+W^- completed
  - two-loop amplitudes for all VV' processes now available
- $gg \to VV'$ at NLO now feasible (formally NNNLO)
- NLO EW corrections are being automated
  - partial results already available
  - phenomenologically relevant
- standard theory precision for all diboson processes will soon be NNLO QCD + NLO EW
- midterm goal: provide a single code to compute all VV' processes at NNLO QCD
- in the meantime: please ask us for available NNLO prediction

Backup slides

$Z\gamma$: ATLAS and CMS setup

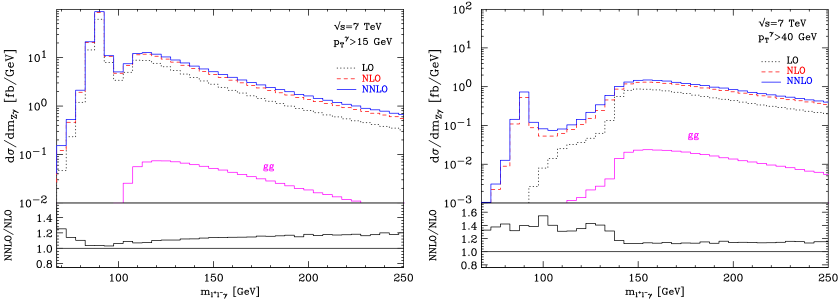
- ATLAS inspired setup [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$ or $p_T^\gamma > 40\,\text{GeV}$, $|\eta^\gamma| < 2.37$, $p_T^\ell > 25\,\text{GeV}$, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40\,\text{GeV}$
  - $\Delta R(\ell, \gamma) > 0.7$
  - $\Delta R(\ell/\gamma, jet) > 0.3$, 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%	

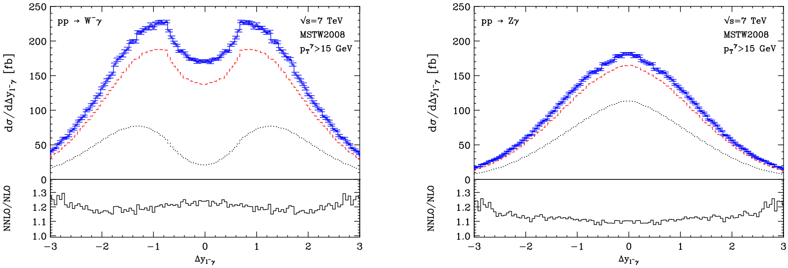
$Z\gamma$: Invariant mass distribution



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

$W\gamma$: 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

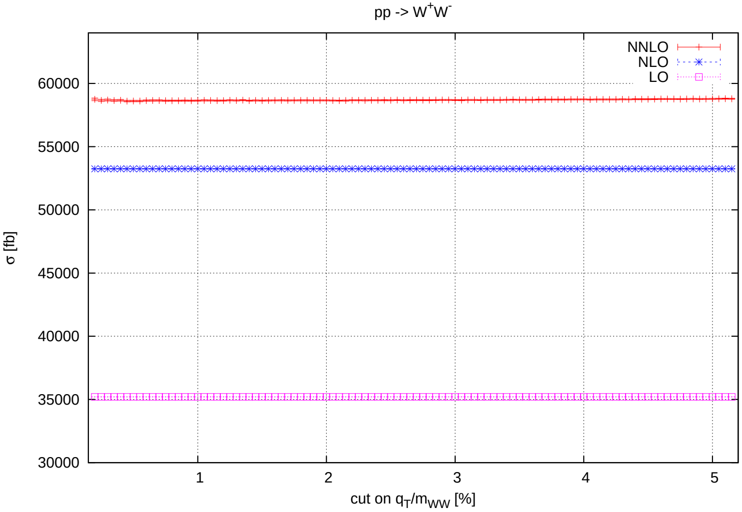
$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

$\sqrt{s}$ [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

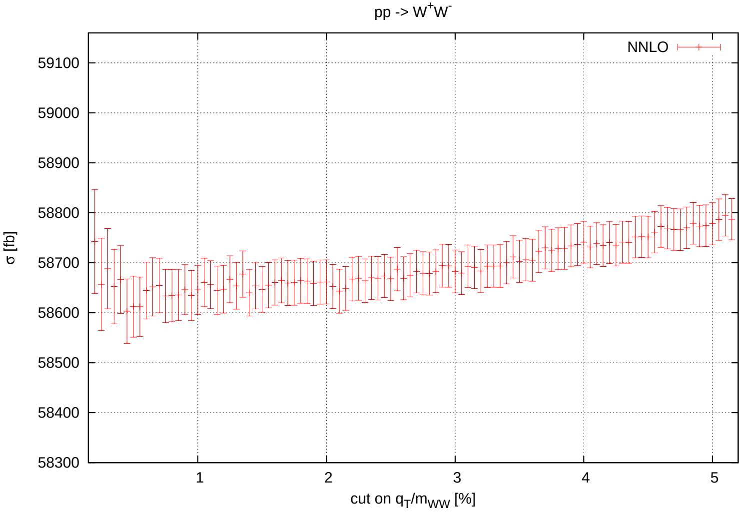
$pp \to W^+W^-$: Stability I

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



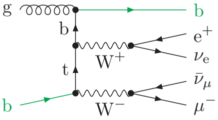
$pp \to W^+W^-$: Stability II

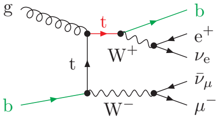
- check independence of phase space regulator (small cut on q_T/Q)



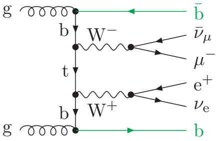
$pp \to W^+W^-$

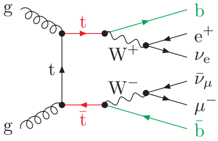
- $\sigma\left(pp \to W^+W^-\right)$ is not well-defined in naive PT
  - at NLO: contribution from $gb \to Wt \to WWb$





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





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

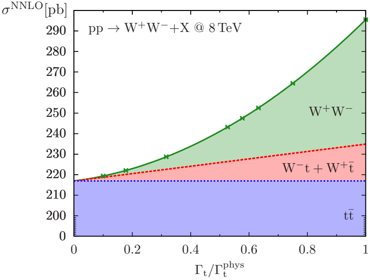
$pp \to W^+W^-$

- 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

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

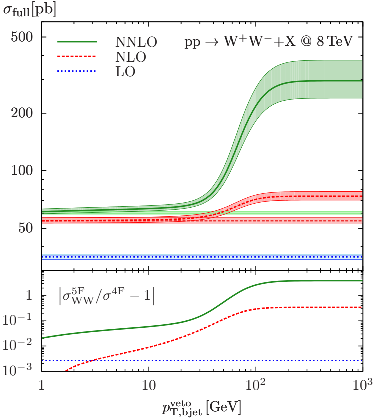
- fit quadratic polynomial to $\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)^2 \sigma_{5FS}\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)$

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



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

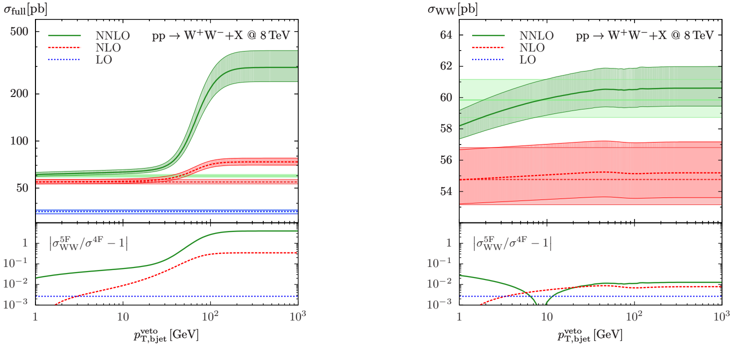
- expect b-jet-veto to suppress the top contamination



- at "typical" $p_{T,\mathrm{bjet}}^{\mathrm{veto}} \sim 30\,\mathrm{GeV}$, about 15% enhancement remains
- $p_{T,\mathrm{bjet}}^{\mathrm{veto}} \to 0$ 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 $p_{T,bjet}^{veto} \approx 30$ GeV, coincides with 4FS result (within $\sim 2\%$)
- logarithmic singularity at small $p_{T,\rm bjet}^{\rm veto}$