NNLO QCD predictions for W^+W^- and ZZ production

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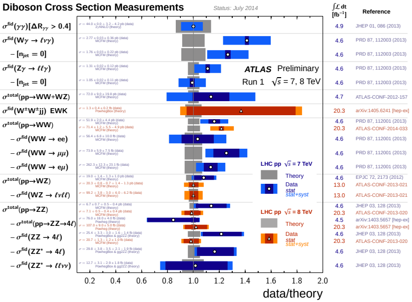
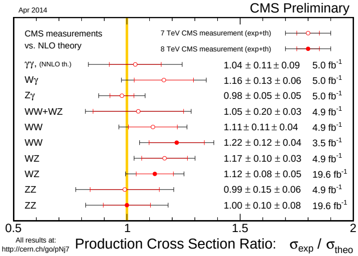
Vector boson pair production

- 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
  - $\to$ NNLO QCD corrections needed



[ATLAS collaboration (2014)]



[CMS collaboration (2014)]

q_T subtraction method I

- consider a process $c\bar{c} \to F$, $c = q$ or $c = g$; final state F is colorless
- then

$$\mathrm{d}\sigma^{\mathrm{F}}_{\mathrm{(N)NLO}}\Big|_{q_T \neq 0} = \mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}}$$

- singular for $q_T \to 0$, but limiting behaviour is known from transverse momentum resummation program [Bozzi, Catani, de Florian, Grazzini (2006)]
- define counterterm $\mathrm{d}\sigma^{\mathrm{CT}} = \Sigma(q_T/Q) \otimes \mathrm{d}\sigma_{\mathrm{LO}}, \quad Q \equiv m_{\mathrm{F}}$
- add $q_T = 0$ piece to obtain the full result:

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

q_T subtraction method II

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

- $\mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{NLO}}$ can be treated by known techniques (Catani-Seymour dipoles, ...)
- $\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right) \Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2 \Sigma^{(2)}(q_T/Q) + \ldots$
- counterterm is universal (up to a NLO process dependence; differs for $c = g$ or $c = q$) and $\Sigma^{(1)}$ and $\Sigma^{(2)}$ are known explicitly
- $\int \left[\mathrm{d}\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}} - \mathrm{d}\sigma^{\mathrm{CT}} \right]$ finite for $q_T/Q \to 0$

q_T subtraction method III

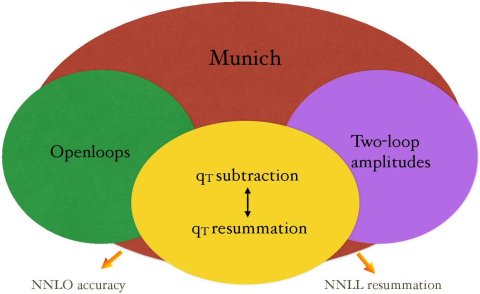
$$d\sigma^{\mathrm{F}}_{\mathrm{(N)NLO}} = \mathcal{H}^{\mathrm{F}}_{\mathrm{(N)NLO}} \otimes d\sigma_{\mathrm{LO}} + \left[d\sigma^{\mathrm{F+jet}}_{\mathrm{(N)LO}} - d\sigma^{\mathrm{CT}}_{\mathrm{(N)NLO}}\right]$$

- $\mathcal{H}^{\mathrm{F}} = \underbrace{1}_{\text{tree level}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{\mathrm{F}(1)}}_{\text{(finite) one-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{\mathrm{F}(2)}}_{\text{(finite) two-loop amplitude}} + \dots$
- $\mathcal{H}^{\mathrm{F}}$ contains the loop corrections to the Born level subprocess
- explicit process independent relations between $\mathcal{H}^{\mathrm{F}(1)}$ [de Florian, Grazzini (2001)], $\mathcal{H}^{\mathrm{F}(2)}$ [Catani, Cieri, de Florian, Ferrera, Grazzini (2013)] and the corresponding renormalized loop amplitudes $\mathcal{M}^{\mathrm{F}}$ are known:

$$\mathcal{H}^{\mathrm{F}(1)} = \mathcal{M}^{\mathrm{F}(1)} - \widetilde{I}^{(1)}(\varepsilon)\mathcal{M}^{\mathrm{F}(0)}$$

$$\mathcal{H}^{\mathrm{F}(2)} = \mathcal{M}^{\mathrm{F}(2)} - \widetilde{I}^{(1)}(\varepsilon)\mathcal{M}^{\mathrm{F}(1)} - \widetilde{I}^{(2)}(\varepsilon)\mathcal{M}^{\mathrm{F}(0)}.$$

The framework



- NLO code: MUNICH [Kallweit]
- tree and one-loop amplitudes: OpenLoops [Cascioli, Lindert, Maierhöfer, Pozzorini]
  see talks by Philipp Maierhöfer and Jonas Lindert
- automated q_T subtraction for NNLO [Bozzi, Catani, Cieri, de Florian, Ferrera, Grazzini], [Kallweit, Grazzini, D.R.]
- automated q_T resummation at NNLL [D.R., Wiesemann]
  $\rightarrow$ Marius Wiesemann's talk

Two-loop amplitudes

- 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 fast numerical implementation of the helicity amplitudes
  $\rightarrow$ talks by Andreas von Manteuffel, Lorenzo Tancredi

- $gg \rightarrow Z\gamma$, $gg \rightarrow ZZ$ and $gg \rightarrow W^+W^-$ loop-induced, $\mathcal{O}\left(\alpha_S^2\right)$
- NLO requires two-loop amplitudes
- contribution between the $\lesssim 1\%$ ($Z\gamma$) and the 5% level (ZZ and W^+W^-)
- now the dominant part of the two-loop amplitudes is known

  [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)]

Applications

- NNLO QCD corrections to diboson production
  - $Z\gamma$ and $W\gamma$ [Grazzini, Kallweit, D.R., Torre; 1309.7000; Grazzini, Kallweit, Rathlev; 1504.01330]
    $\rightarrow$ Stefan Kallweit's talk
  - on-shell ZZ [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi, Weihs; 1405.2219]
  - on-shell W^+W^- [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi; 1408.5243]
  - $ZZ \rightarrow 4\ell$ [Grazzini, Kallweit, D. R.; (2015)
- NNLL resummation of transverse momentum spectra
  - on-shell ZZ and W^+W^- [Grazzini, Kallweit, D. R., Wiesemann; (2015)]
    $\rightarrow$ Marius Wiesemann's talk
  - in principle available for all processes completed at NNLO

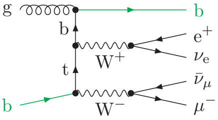
$pp \to W^+W^-$

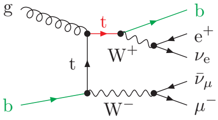
- WW production one of the most important diboson processes
- $\sim 2\sigma$ excess in ATLAS and CMS measurements over NLO QCD
- experimentally challenging due to large top background
- top background gets suppressed by jet veto
- top-subtracted fiducial cross section gets extrapolated back to total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

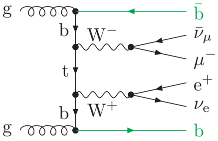
$pp \to W^+W^-$

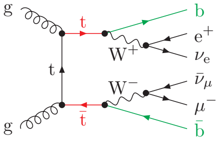
- $\sigma\left(pp \to W^+W^-\right)$ is not well-defined in naive PT
  - at NLO: contribution from $gb \to Wt \to WWb$





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





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

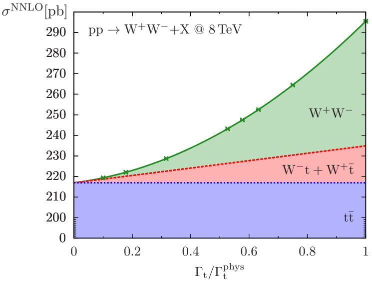
$pp \to W^+W^-$

- 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

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

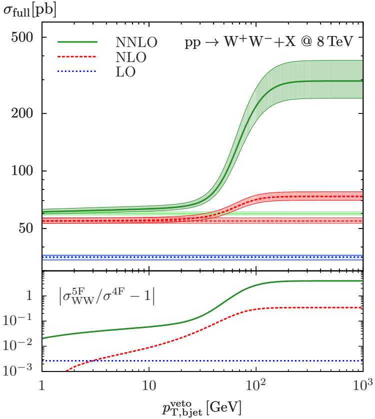
- fit quadratic polynomial to $\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)^2 \sigma_{5FS}\left(\Gamma_t/\Gamma_t^{\mathrm{phys}}\right)$

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



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

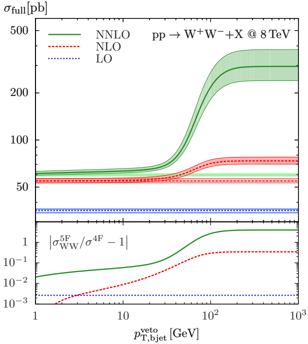
- expect b-jet-veto to suppress the top contamination



- at "typical" $p_{T,\rm bjet}^{\rm veto} \sim 30\,\text{GeV}$, about 15% enhancement remains
- $p_{T,\rm bjet}^{\rm veto} \to 0$ 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]

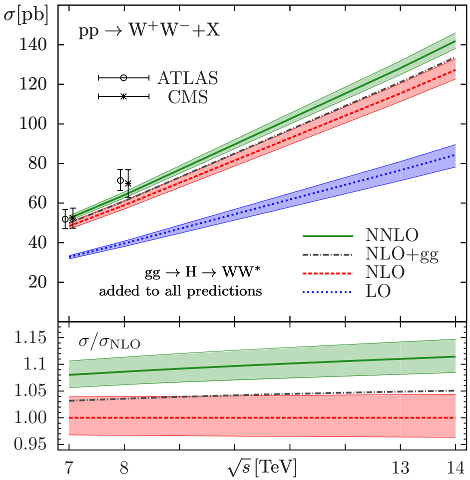
- σ_{WW} should not change when applying a b-jet veto if properly defined



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

W^+W^-: the inclusive cross section

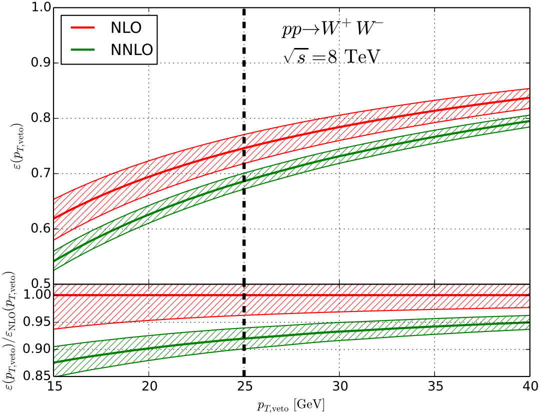
[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi; 1408.5243]



- 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

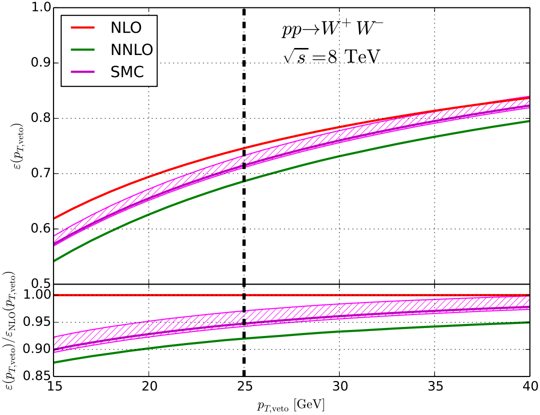
[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



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

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

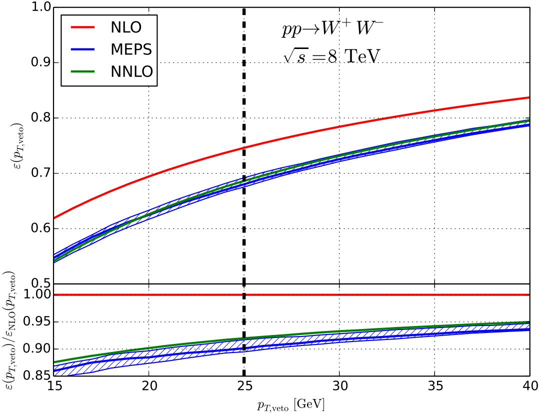
[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- NLO+PS lowers efficiency
- marginally consistent with NNLO

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

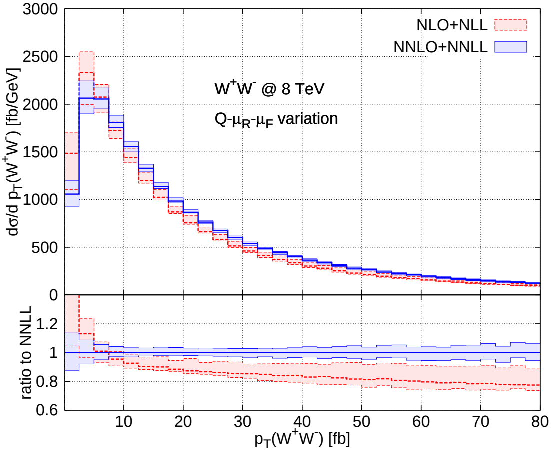
[Grazzini, Kallweit, Moretti, Pozzorini, D. R.; preliminary]



- first emission with NLO accuracy
- only $\sim -3\%$ effect w.r.t. NNLO
- missing higher log effects?

$pp \to W^+W^-$: resummed p_T spectrum

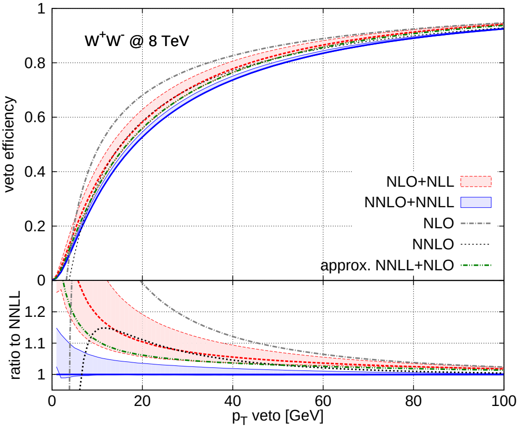
[Grazzini, Kallweit, D. R., Wiesemann; preliminary]



- spectrum hardens when resumming higher logs
- expect effect on jet veto efficiency

$pp \to W^+W^-$: resummed p_T spectrum

[Grazzini, Kallweit, D. R., Wiesemann; preliminary]

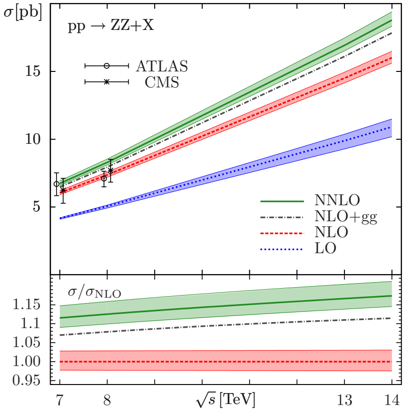


- effect on p_T veto efficiency $\sim -5\%$ w.r.t NNLO, $\sim -3\%$ w.r.t. approx. NNLL+NLO
- $\to$ Marius Wiesemann's talk for more details

$pp \to ZZ$

- results for on-shell ZZ production at NNLO [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi, Weihs; 1405.2219]

- NNLO corrections range from 11% to 17%
- gg fusion contribution is about 60% of the NNLO correction
- experiments set mass cuts on $m_{\ell\ell}$ to isolate resonant contribution
  $\to$ not possible in on-shell computation



$pp \to ZZ$: off-shell effects

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

- present results at 8 TeV with 66 GeV $< m_{\ell^+\ell^-} <$ 116 GeV (ATLAS) and 60 GeV $< m_{\ell^+\ell^-} <$ 120 GeV (CMS)

pb	LO	NLO	NLO+gg	NNLO	measured
ATLAS	4.98	6.86	7.36	7.67	7.1 ± 0.6
CMS	5.06	6.98	7.48	7.78	7.7 ± 0.8

- ATLAS fiducial region: mass cuts, $p_T^\ell > 7$ GeV, $|\eta^\ell| < 2.7$, $\Delta R(\ell, \ell) > 0.2$

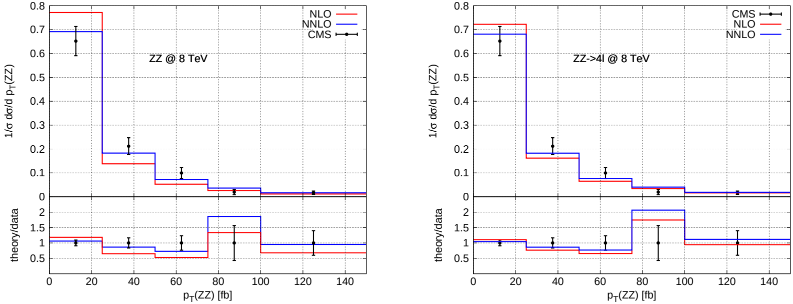
fb	LO	NLO	NLO+gg	NNLO	ATLAS
ATLAS $ee\mu\mu$	$6.95^{+0.46}_{-0.61}$	$9.86^{+0.54}_{-0.35}$	$10.72^{+1.11}_{-0.76}$	$11.2^{+0.78}_{-0.60}$	11.1 ± 1.3

- excellent agreement with NNLO, but experimental uncertainties still large

$pp \to ZZ$: off-shell effects

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

- CMS fiducial region: mass cuts, $p_T^\mu > 5\,\text{GeV}$, $p_T^e > 7\,\text{GeV}$, $|\eta^\mu| < 2.4$, $|\eta^e| < 2.5$
- all distributions normalized to fiducial cross section
- study impact on $p_T(ZZ)$ spectrum

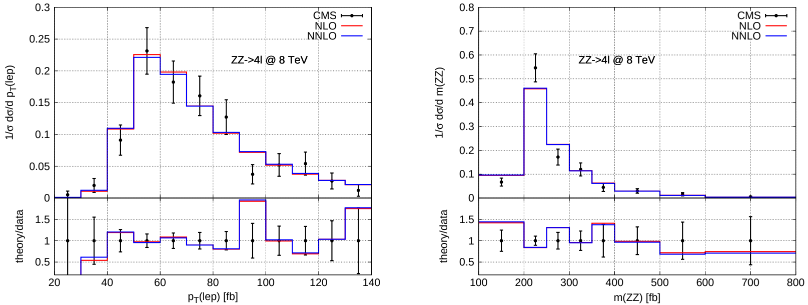


- slightly harder spectrum
- good agreement with NNLO
- see Marius Wiesemann's talk for resummed spectrum

$pp \to ZZ$: off-shell effects

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

- p_T of the hardest lepton, 4 lepton invariant mass

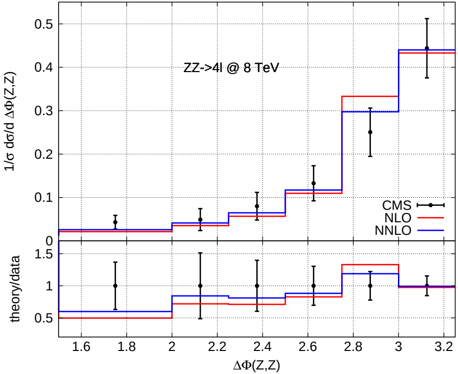


- small corrections in normalized distributions
- experimental uncertainties still large

$pp \to ZZ$: off-shell effects

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

- $\Delta\Phi$ between the two reconstructed Z bosons



- at LO localized at $\Delta\Phi = \pi$
  $\Rightarrow$ expect corrections to skew distribution to lower values
- agreement with data improved

Summary and outlook

- significant progress on the NNLO QCD corrections to diboson production
  - $\gamma\gamma$, $Z\gamma$ and $W^{\pm}\gamma$ completed
  - on-shell ZZ and W^+W^- completed
  - two-loop amplitudes for all VV' processes now available
  - first NNLO results $VV' \to 4\ell$ presented
- code extended to perform NNLL+NNLO p_T resummation
  - first application: W^+W^- and ZZ
  - relevant for the $p_T(W^+W^-)$ reweighting used by CMS
  - can be extended to include selection cuts on the leptons
- 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 $\varepsilon = 0.5$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$

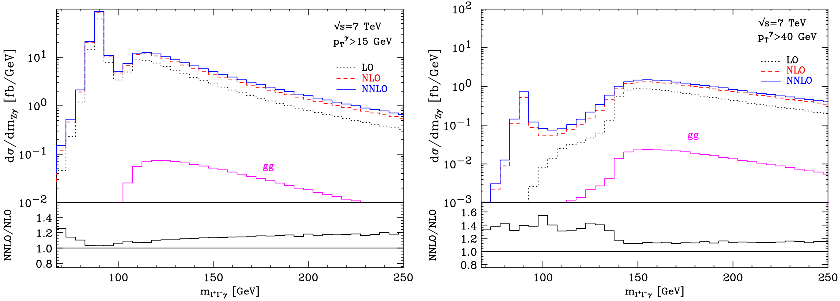
- CMS inspired setup [CMS collaboration (2013)]
  - $p_T^\gamma > 15\,\text{GeV}$, $|\eta^\gamma| < 2.5$, $p_T^\ell > 20\,\text{GeV}$, $|\eta^\ell| < 2.5$
  - $m_{\ell\ell} > 50\,\text{GeV}$
  - $\Delta R(\ell, \gamma) > 0.7$
  - smooth cone isolation with $\delta_0 = 0.15$ and $\varepsilon = 0.05$
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

$Z\gamma$: 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%	

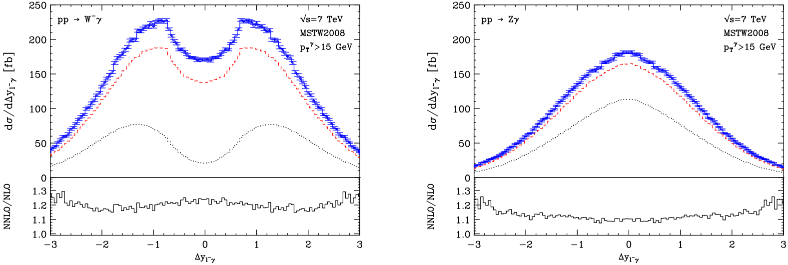
$Z\gamma$: Invariant mass distribution



- 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

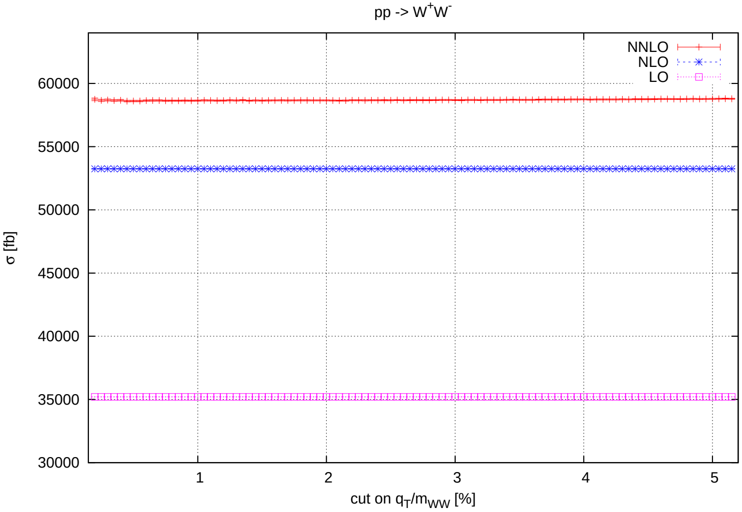
$pp \to W^+W^-$ [T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi; 1408.5243]

$\sqrt{s}$ [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)