Diboson production in NNLO QCD

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based on 1309.7000, 1405.2219, 1408.5243

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Outline

1. Technicalities
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3. Results for $pp \to W^\pm\gamma \to \ell^\pm\nu_\ell\gamma$
4. Results for $pp \to ZZ$
5. Results for $pp \to W^+W^-$
6. Conclusion

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

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

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, D.R., 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, D. R., 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

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

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

Photon isolation

- two contributions to photon production:
  - direct production in the hard process, e.g. genuine $\ell^+\ell^-\gamma$ production
  - non-perturbative fragmentation of a hard parton
- in experiments, impose hard cone isolation: $\sum_{\delta<R} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma$
- only infrared safe when combined with fragmentation contribution due to quark-photon collinear singularity
- smooth cone isolation [Frixione (1998)]: define $\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R)}\right)^n$,

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

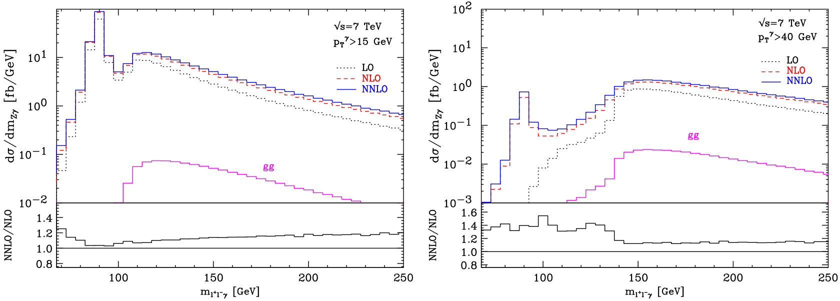
- smooth cone isolation eliminates fragmentation contribution completely

$Z\gamma$: Setup and cross sections

- we present results for $pp \to \ell^+\ell^-\gamma + X$ [M. Grazzini, S. Kallweit, D. R., A. Torre; 1309.7000]
- 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)

$W\gamma$: 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

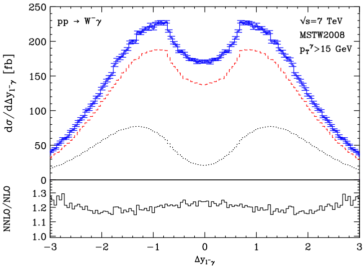
- setup close to the ATLAS analysis [ATLAS collaboration (2013)]
  same setup as for $Z\gamma$, except for
  - $m_{\ell\ell} > 40$ GeV $\rightarrow$ $p_{T,miss} > 35$ GeV

- **preliminary:** [M. Grazzini, S. Kallweit, D. R., A. Torre]

		LO	NLO	NNLO	exp.
W^+	σ [pb]	0.511(1)	1.155(1)	1.371(5)	
	rel. correction		126%	19%	
W^-	σ [pb]	0.395(1)	0.910(1)	1.085(4)	
	rel. correction		130%	19%	
total	σ [pb]	0.906(1)	2.065(1)	2.456(6)	2.770(340)
	rel. correction		128%	19%	

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

- naively: couplings larger for $W\gamma$ than for $Z\gamma$
- however: gauge cancellation for $W\gamma \Rightarrow$ partonic tree-level amplitude vanishes at $\cos\theta^* = \pm\frac{1}{3}$
- gets filled up by real radiation corrections (and by FSR contribution)



Scale uncertainties

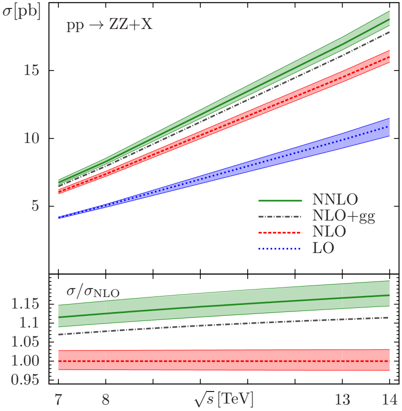
- *symmetric* scale variations around $\mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2}$ tiny at NLO due to an accidental cancellation
- follow suggestion by MCFM authors and vary $\mu_R = a\mu_0,\ \mu_F = \mu_0/a,\ a \in [0.5,2]$ [Campbell, Ellis, Williams (2011)]

σ [fb]	LO	NLO	NNLO
$Z\,(\to \ell^+\ell^-)\,\gamma$	$850.7^{+7\%}_{-9\%}$	$1226.2^{+4\%}_{-5\%}$	$1308^{+1\%}_{-2\%}$
$Z\,(\to \nu\overline{\nu})\,\gamma$	$27.64^{+1\%}_{-2\%}$	$41.63^{+4\%}_{-3\%}$	$46.3^{+3\%}_{-2\%}$
$W^+\gamma$	$511.0^{+6\%}_{-7\%}$	$1155.3^{+7\%}_{-7\%}$	$1371^{+5\%}_{-4\%}$
$W^-\gamma$	$395.3^{+6\%}_{-8\%}$	$909.9^{+7\%}_{-7\%}$	$1085^{+4\%}_{-4\%}$

$pp \to ZZ$

- two-loop amplitudes have recently been computed
  [Henn, Melnikov, Smirnov (2014); Gehrmann, von Manteuffel, Tancredi, Weihs (2014)]
- results for on-shell ZZ production at NNLO [F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. R., L.Tancredi, E. Weihs; 1405.2219]

- NNLO corrections range from 11% to 17%
- gg fusion contribution is about 60% of the NNLO correction



$pp \to W^+W^-$

- 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

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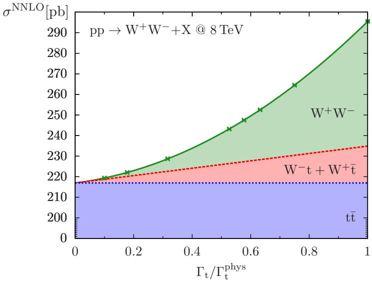
$pp \to W^+W^-$

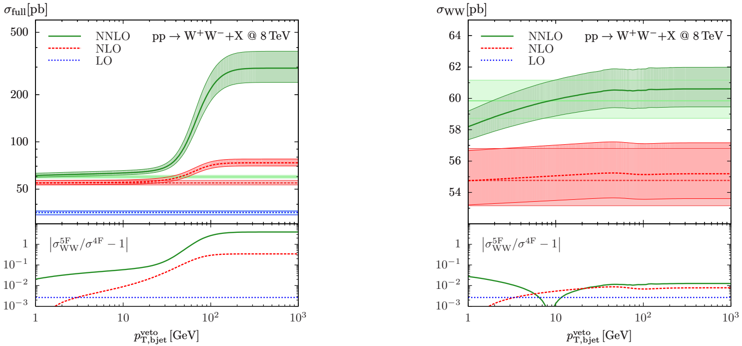
- $\sigma\,(pp \to W^+W^-)$ is not well-defined in naive PT
  - at NLO: single real correction receives contribution from $gb \to Wt \to WWb$
  - at NNLO: double real correction receives contribution from $q\bar{q}/gg \to t\bar{t} \to WWb\bar{b}$
  - cannot consistently be removed in 5FS, due to collinear singularities
- WW cross section is well-defined in 4FS, 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
  $\Rightarrow$ fit to obtain decomposition

$$\sigma_{full} = \sigma_{WW} + \sigma_{Wt} + \sigma_{tt}$$



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

- σ_{WW} defined in this way should not change when applying a b-jet veto



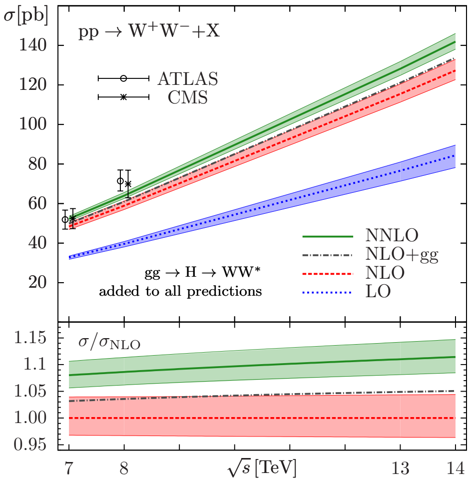
- σ_{WW} is stable above $p_{T,bjet}^{veto} = 30\,\text{GeV}$, coincides with 4FS result (within $\sim 2\%$)
- logarithmic singularity at small $p_{T,bjet}^{veto}$

$pp \to W^+W^-$ [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

$pp \to W^+W^-$ [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

- 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 $Z\gamma$ (radiation zero!)
    - loop-induced *gg* contribution very small
- inclusive on-shell production of ZZ at NNLO
    - *gg* contribution about 60% of NNLO corrections
    - already useful, e.g. for Higgs width determination
- inclusive on-shell production of WW at NNLO
    - *gg* contribution about 35% of NNLO corrections
    - 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
      [F. Caola, J. Henn, K. Melnikov, A. Smirnov, V. Smirnov (2014); Ch. Anastasiou, J. Cancino, F. Chavez, C. Duhr, A. Lazopoulos, B. Mistlberger, R. Mueller (2014)]

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 $\varepsilon = 0.5$
    - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$

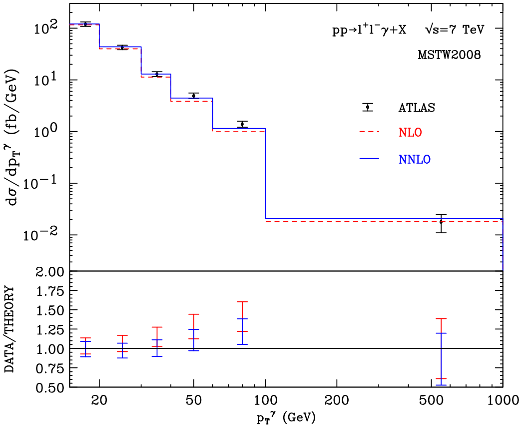
- CMS inspired setup [CMS collaboration (2013)]
    - $p_T^\gamma > 15\,\text{GeV}$, $|\eta^\gamma| < 2.5$, $p_T^\ell > 20\,\text{GeV}$, $|\eta^\ell| < 2.5$
    - $m_{\ell\ell} > 50\,\text{GeV}$
    - $\Delta R(\ell, \gamma) > 0.7$
    - smooth cone isolation with $\delta_0 = 0.15$ and $\varepsilon =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

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

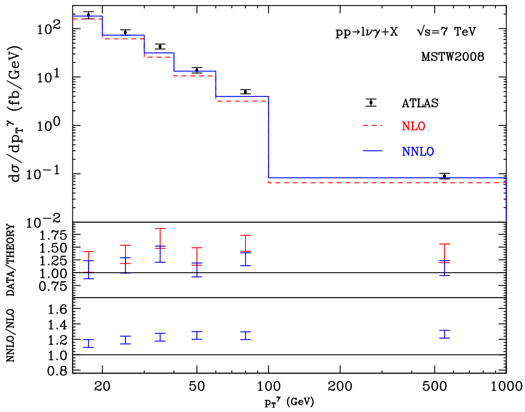
- $q\overline{q}$ the dominant channel at each order and also has the largest corrections
- gq and $g\overline{q}$ have negative weight
- gg is tiny

$Z\gamma$: Comparison with data



- NNLO effect grows with p_T
- agreement with data slightly improved

$W\gamma$: Comparison with data



- NNLO effect grows with p_T
- agreement with data improved