Vector boson pair production in NNLO QCD

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Outline

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Motivation

- fully exclusive NNLO QCD calculations are desirable for several reasons
  - increased accuracy
  - reduced scale dependence
  - more realistic jet treatment
  - in some regions, NLO is effectively LO
  - all partonic channels consistently included

- available fully exclusive NNLO computations:
  - $pp \to H$ [Anastasiou, Melnikov, Petriello (2005); Catani, Grazzini (2007)]
  - $pp \to V$ [Melnikov, Petriello (2006); Catani, Cieri, Ferrera, de Florian, Grazzini (2009)]
  - $e^+e^- \to$ three jets [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich (2007)]
  - $pp \to WH$ [Ferrera, Grazzini, Tramontano (2011)]
  - $pp \to \gamma\gamma$ production [Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
  - $pp \to$ dijet (gg channel) [Gehrmann-De Ridder, Gehrmann, Glover, Pires (2013)]
  - $pp \to t\bar{t}$ (total cross section presented) [Czakon, Mitov (2012); Czakon, Fiedler, Mitov (2013)]
  - $pp \to H +$ jet (gg channel) [Boughezal, Caola, Melnikov, Petriello, Schulze (2013)]

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

	$\sigma\,(pp \to W^+W^- + X)$ [pb]	SM NLO [pb]
ATLAS 7 TeV	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
CMS 7 TeV	$52.4 \pm 2.0 \pm 4.5 \pm 1.2$	$44.7^{+2.1}_{-1.9}$
CMS 8 TeV	$69.9 \pm 2.8 \pm 5.6 \pm 3.1$	$57.3^{+2.4}_{-1.6}$

Status of $pp \to VV'$

- NNLO QCD calculation of $\gamma\gamma$ done [Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
- next step: $Z\gamma$ and $W\gamma$
  - QCD NLO corrections available [Ohnemus (1993); Baur, Han, Ohnemus (1998); de Florian, Signer (2000); Campbell, Ellis, Williams (2011)]
  - loop-induced gg contribution [Ametller, Gava, Paver, Treleani (1985); van der Bij, Glover (1988); Adamson, de Florian, Signer (2003)]
  - electroweak corrections available [Hollik, Meier (2004); Accomando, Denner, Meier (2006)]
- necessary ingredients:
  - $pp \to V\gamma + 2$ partons at tree level, available
  - $pp \to V\gamma + 1$ parton at one loop, available [Campbell, Hartanto, Williams (2012)]
  - $pp \to V\gamma$ at two loops, available [Matsuura, van der Marck, van Neerven (1989); Gehrmann, Tancredi (2012)]
  - $gg \to V\gamma$ loop-induced, available
- we obtain tree- and one-loop amplitudes from OpenLoops + Collier library [Cascioli, Maierhofer, Pozzorini (2012); Denner, Dittmaier, Hofer; Denner, Dittmaier (2005)]
- MC generator: inhouse solution [Kallweit]
- use q_T subtraction [Catani, Grazzini (2007)] for handling of IR divergences

q_T subtraction method I

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

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

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

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

q_T subtraction method II

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

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

q_T subtraction method III

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

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

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

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: $\sum_{\delta<\delta_0} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma$
- only infrared safe when combined with fragmentation contribution due to quark-photon collinear singularity
- smooth cone isolation [Frixione (1998)]: define $\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(\delta_0)}\right)^n$,

$$\sum_{\delta'<\delta} E_T^{had} \leq \varepsilon_\gamma E_T^\gamma \, \chi(\delta) \quad \text{for all} \quad \delta \leq \delta_0$$

- smooth cone isolation eliminates fragmentation contribution completely

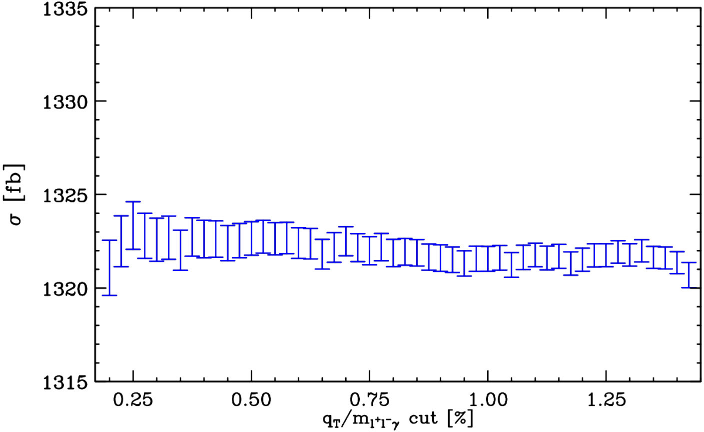
$Z\gamma$: Setup and cross sections

- we present results for $pp \to \ell^+\ell^-\gamma + X$
- 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
    - $\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\ell/\gamma, jet) > 0.3$
- cross sections:

		LO	NLO	NNLO	exp.
$p_T^\gamma > 15$ GeV	σ [pb]	0.851(1)	1.226(1)	1.323(3)	1.31(12)
	rel. correction		44%	8%	
$p_T^\gamma > 40$ 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%	

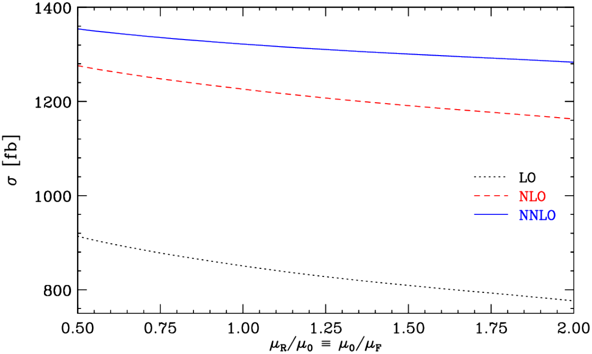
Stability

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



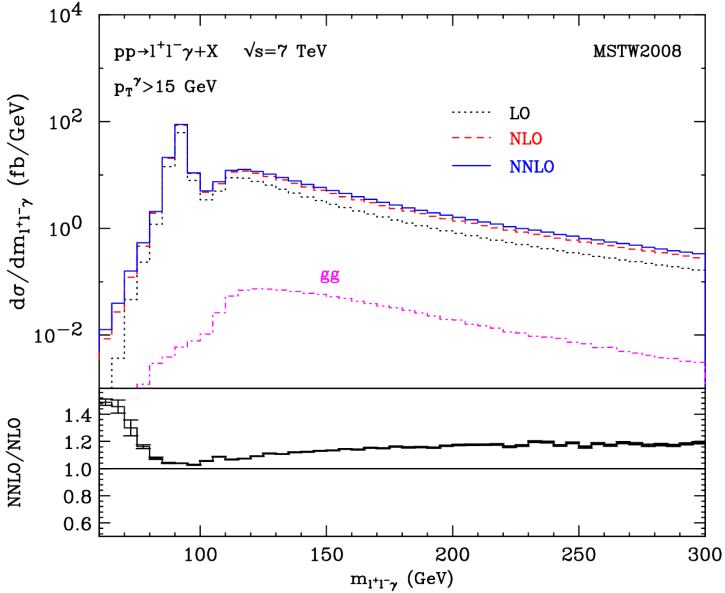
Scale uncertainty

- check scale variation; tiny at NLO due to an accidental cancellation
- follow proposition by [Campbell, Ellis, Williams (2011)] and vary $\mu_R = a\mu_0$, $\mu_F = \mu_0/a$, $a \in [0.5,2]$

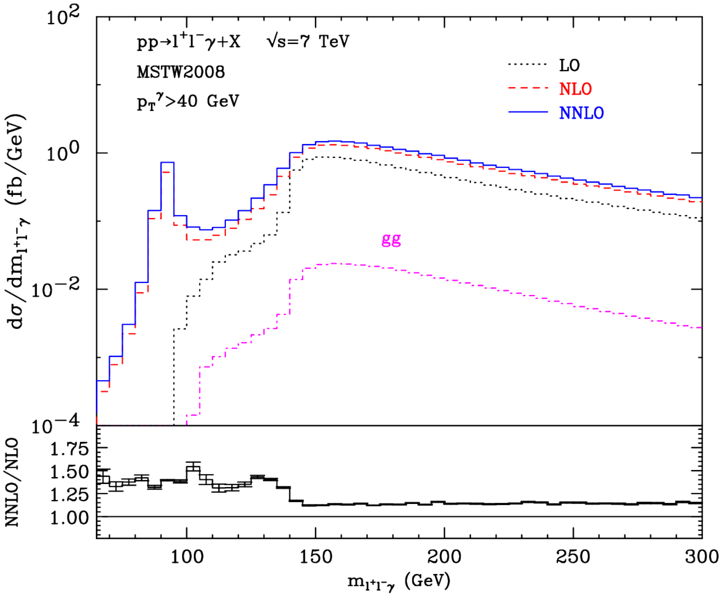


LO	NLO	NNLO
+7% −9%	+4% −5%	+2% −2%

Invariant mass distribution, $p_T^\gamma > 15\,\text{GeV}$



Invariant mass distribution, $p_T^\gamma > 40\,\text{GeV}$



$W\gamma$ measurement

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

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

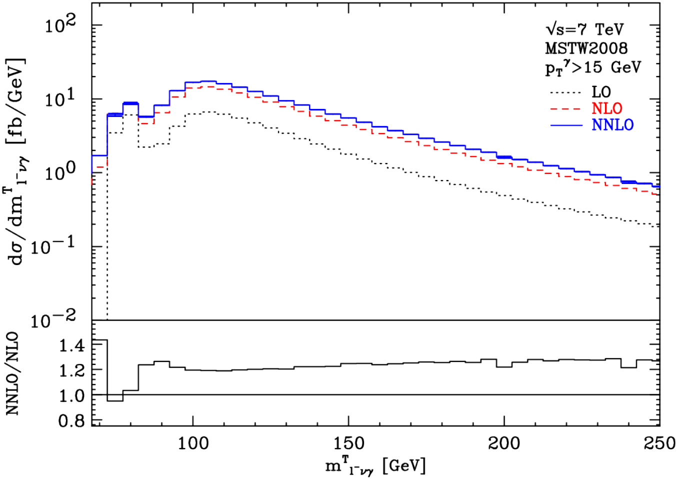
- could be a NNLO effect

$W\gamma$: 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:** $V_{CKM} = \mathbb{1}$, partially unchecked

		LO	NLO	NNLO	exp.
W^+	σ [pb]	0.511(1)	1.154(1)	1.395(9)	
	rel. correction		126%	21%	
W^-	σ [pb]	0.395(1)	0.908(2)	1.093(8)	
	rel. correction		130%	20%	
total	σ [pb]	0.906(1)	2.062(2)	2.488(12)	2.77(34)
	rel. correction		128%	20%	

Transverse mass distribution, $p_T^\gamma > 15\,\mathrm{GeV}$



Conclusion

- results for fully differential NNLO QCD computation of $Z\gamma$ production
  - good apparent convergence of perturbative series (e.g. ATLAS cuts: $K_{NNLO/NLO} = 1.08$, $K_{NLO/LO} = 1.44$)
  - K factor not uniform and strongly cut dependent. Corrections can vary between 7% and 16% for typical LHC cuts
  - loop-induced gg contribution very small, does not capture most of the NNLO correction
  - more phenomenology will follow
  - $pp \to Z\gamma \to \nu_\ell \overline{\nu}_\ell \gamma$ to be done, simpler than $Z\gamma \to \ell^+\ell^-\gamma$

- first results for $W\gamma$ production
  - NNLO corrections are $\sim 20\%$
  - more detailed studies to follow

$Z\gamma$: ATLAS and CMS setup

- ATLAS inspired setup [ATLAS collaboration (2013)]
  - $p_T^\gamma > 15\,\mathrm{GeV}$ or $p_T^\gamma > 40\,\mathrm{GeV}$, $|\eta^\gamma| < 2.37$, $p_T^\ell > 25\,\mathrm{GeV}$, $|\eta^\ell| < 2.47$
  - $m_{\ell\ell} > 40\,\mathrm{GeV}$
  - $\Delta R(\ell,\gamma) > 0.7$
  - $\Delta R(\ell/\gamma, jet) > 0.3$, where $E_T^{jet} > 30\,\mathrm{GeV}$ 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)]
  - $p_T^\gamma > 15\,\mathrm{GeV}$, $|\eta^\gamma| < 2.5$, $p_T^\ell > 20\,\mathrm{GeV}$, $|\eta^\ell| < 2.5$
  - $m_{\ell\ell} > 50\,\mathrm{GeV}$
  - $\Delta R(\ell,\gamma) > 0.7$
  - 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	1364	-16	-38	6	6	1	1323

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

p_T^γ distribution, $p_T^\gamma > 15\,\text{GeV}$