Progress towards vector boson pair production in NNLO QCD

Dirk Rathlev
with M. Grazzini, S. Kallweit, A. Torre

Universität Zürich

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Outline

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
  - realistic studies with experimental cuts

- available 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) [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 [Amettler, 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:

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

q_T subtraction method II

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

- $\mathcal{H}^F = \underbrace{1}_{\text{tree level}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)}}_{\text{(finite) one-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)}}_{\text{(finite) two-loop amplitude}} + \ldots$
- $\mathrm{d}\sigma^{F+jets}_{NLO}$ can be treated by known techniques (Catani-Seymour dipoles, ...)
- $\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right) \Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2 \Sigma^{(2)}(q_T/Q) + \ldots$
- counterterm is universal (only depends on whether $c = g$ or $c = q$) and $\Sigma^{(1)}$ and $\Sigma^{(2)}$ are known in both cases

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

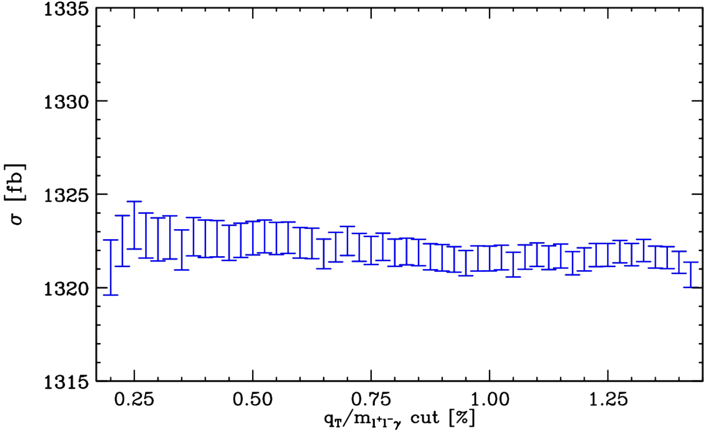
Setup and cross sections

- 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
  - $\Delta R(\ell, \gamma) > 0.7$
  - $\Delta R(\ell/\gamma, jet) > 0.3$, where $E_T^{jet} > 30$ 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 $\varepsilon = 0.5$
  - $\mu_R = \mu_F = \sqrt{m_Z^2 + (p_T^\gamma)^2}$
- cross sections:

		LO	NLO	NNLO	exp.
$p_T^\gamma > 15$ GeV	σ [pb]	0.851(1)	1.226(1)	1.325(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)	
	rel. correction		42%	7%	

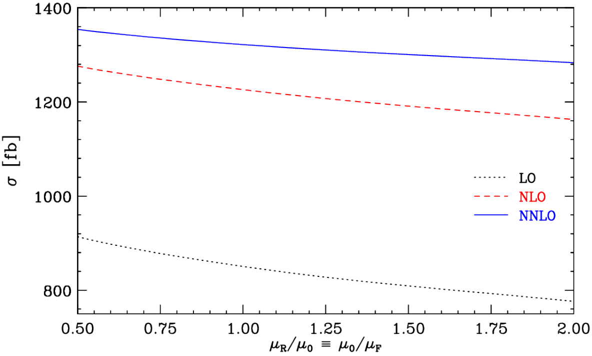
Stability

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



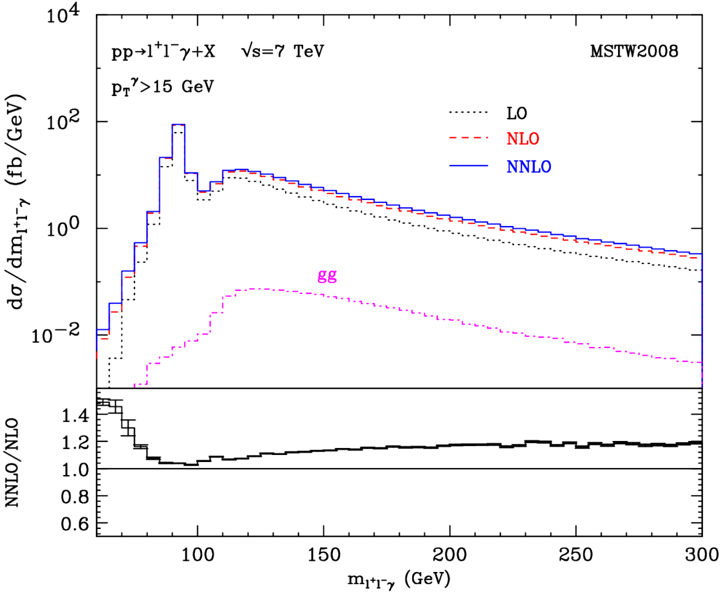
Scale uncertainty

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

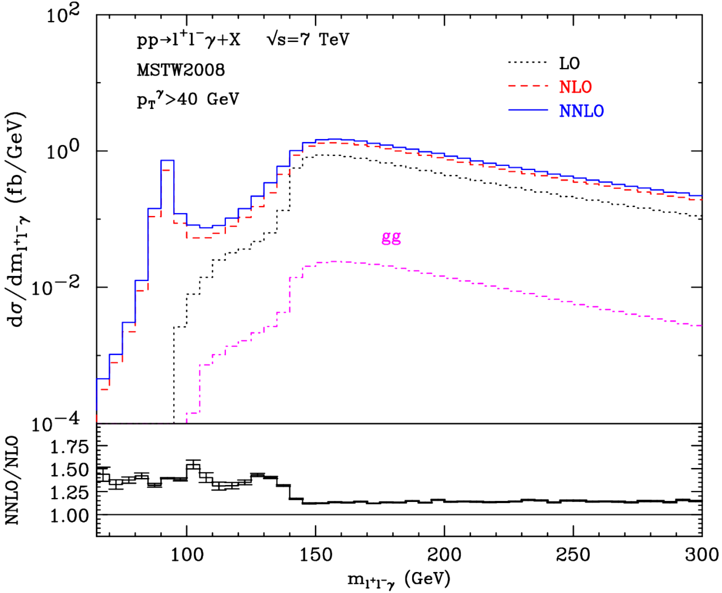


LO	NLO	NNLO
$+7\%$ -9%	$+4\%$ -5%	$+2\%$ -2%

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



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



Conclusion

- first 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
- next goal: $W\gamma$ production. No additional complications expected
- more phenomenology will follow

Contributions by channel

	$q\bar{q}$	gq	$g\bar{q}$	gg	qq	$\bar{q}\bar{q}$	total [fb]
LO	851						851
NLO	1255	-6	-23				1226
NNLO	1364	-16	-38	6	6	1	1323

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

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