QCD corrections to vector boson pair production in gluon fusion at the LHC

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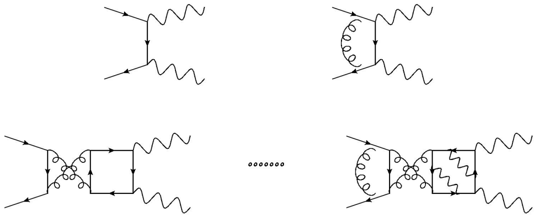
Based on collaboration with *Thomas Gehrmann*, *Andreas von Manteuffel*, *Fabrizio Caola*, *Kirill Melnikov*, *Raoul Röntsch*

See: [arXiv:1503.04812], [arXiv:1503.08835], [arXiv:1509.06734],[arXiv:1511.08617]

What is **vector boson pair production**?

We mean the production of **pairs** of **electroweak vector bosons** V_1, V_2:

$$V_1\,V_2 = \{\,\gamma\,\gamma\,, \qquad Z\,\gamma\,,\;\; W^{\pm}\,\gamma\,, \qquad Z\,Z\,,\;\; W^{+}W^{-}\,, \qquad W^{\pm}Z\,\}$$



Importance - Higgs background, new physics searches, and so on

$$\Downarrow$$

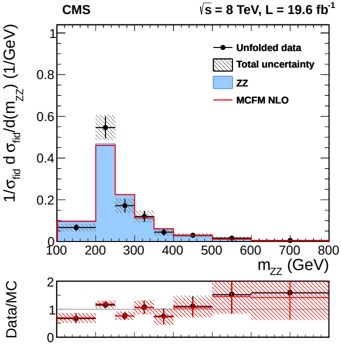
- Fundamental channel for **Higgs discovery** and study of its properties

- Fundamental background for many new physics searches

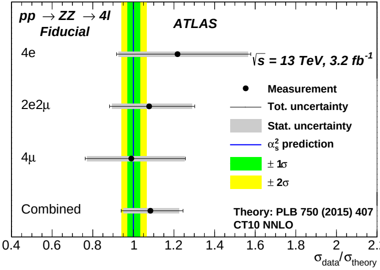
- Check of electroweak sector of SM, anomalous gauge couplings, etc...

Experimental status

First LHC run 2010-2013. **Run 2** is ongoing, new results at ICHEP 2016
many events for $\{\gamma\,\gamma, Z\,\gamma, W^{\pm}\,\gamma, Z\,Z, W^{+}W^{-}, ...\}$ production:



$Z\,Z$ production at *CMS*



$Z\,Z$ production at ATLAS

Target Precision LHC $\rightarrow$ 5 – 3%

At the **LHC** $V_1 V_2$ pairs are produced through **two main partonic subchannels**

$q\,\bar{q} \to V_1 V_2$, (known to **NNLO**)

$g\,g \to V_1 V_2$, (known to **NLO**)

N^3LO in $pp \to VV$

Do we really need to go so high in perturbation theory?

Fully inclusive cross-sections[1]

	$\sigma^{q\bar{q}}_{NLO}$ [pb]	$\sigma^{q\bar{q}}_{NNLO}$ [pb]	$\sigma^{gg}_{LO}/(\sigma^{q\bar{q}}_{NNLO} - \sigma^{q\bar{q}}_{NLO})$
ZZ 13 TeV	$14.5 \pm 3\%$	$16.9 \pm 3\%$	$\approx 60\%$
WW 13 TeV	$106.0 \pm 3.5\%$	$118.7 \pm 3\%$	$\approx 35\%$

[1] NNLO PDFs, $\mu_{R,F} = m_Z, m_W$ respectively, variation $0.5 m_V < \mu_{R,F} < 2\, m_V$

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NNLO corrections are in both cases between 12-15%.

gg channel (LO) constitutes a relevant fraction of it.
In the two cases $\approx$ 3-7% of **total NNLO**!

Clearly, **NNLO** in $q\bar{q}$ channel is <u>crucial</u> for reliable results with $\approx 3\%$ precision
$\rightarrow$ theory uncertainty does NOT decrease

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What do we need for $g\, g \to V_1 V_2$ @ **NLO** ?

$$\sigma_{NLO}^{ggVV} = \int d\phi_{VV}\, |\mathcal{M}^{(1)*}_{ggVV} \mathcal{M}^{(2)}_{ggVV}| \quad \Rightarrow \quad \text{Last missing piece}$$

$$+ \int d\phi_{VVj}\, |\mathcal{M}^{(1)*}_{ggVVj} \mathcal{M}^{(1)}_{ggVVj}|$$

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Numerical unitarity for real radiation
Need stable code in soft-collinear limit!

The two pieces are individually divergent. Can be put together using any **NLO** subtraction scheme. We used FKS and also the q_T scheme!

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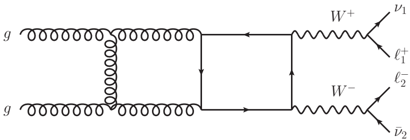

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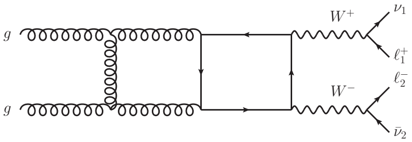

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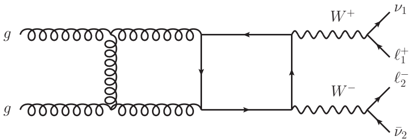

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Putting everything together – we consider

$$g\,g \to ZZ \to e^+e^-\,\mu^+\mu^- \qquad g\,g \to WW \to e^-\nu_e\,\mu^+\bar{\nu}_\mu$$

a) First phenomenology application to the production of four leptons

a.1) @ 8 TeV LHC
a.2) @ 13 TeV LHC

b) We produce the Z/W *almost on-shell* using **Breit-Wigner** distributions

c) We use NNPDF3.0 pdfs

c.1) LO α_s running for one-loop amplitude
c.2) NLO α_s running for two-loop amplitude

d) Slightly different analysis in the two cases

The case of $g\,g \to ZZ \to e^+e^-\,\mu^+\mu^-$

1) We require $60\text{GeV} < m_{l\bar{l}} < 120\text{GeV}$
2) We use $\mu = \mu_R = \mu_F = 2\,m_Z$ as **central value**. Uncertainty estimate varying between $\mu = m_Z$ and $\mu = 4\,m_Z$.

As expected we find very large radiative corrections

- @ 8 TeV

$$\sigma_{\rm LO}^{gg\to ZZ} = 0.97^{+0.3}_{-0.2}\ \text{fb}, \quad \sigma_{\rm NLO}^{gg\to ZZ} = 1.8^{+0.2}_{-0.2}\ \text{fb},$$

- @ 13 TeV

$$\sigma_{\rm LO}^{gg\to ZZ} = 2.8^{+0.7}_{-0.6}\ \text{fb}, \quad \sigma_{\rm NLO}^{gg\to ZZ} = 4.7^{+0.4}_{-0.4}\ \text{fb}.$$

We find an increase of $\mathcal{O}(60\% - 110\%)$ @ 8 TeV
and an increase of $\mathcal{O}(40\% - 90\%)$ @ 13 TeV[2]

[2]Note upper value is $\mu = m_Z$, lower value is $\mu = 4m_Z$

The case of $g\,g \to W^+W^- \to e^-\nu_e\,\mu^+\bar{\nu}_\mu$

1) Scale $\mu = \mu_R = \mu_F = m_W$ as **central value**. Uncertainty estimate varying between $\mu = m_W/2$ and $\mu = 2\,m_W$.

2) We compute **fiducial cross section** following Monni, Zanderighi '14 for direct comparison with experiment.

3) What about third generation? Here we **cannot decouple** *top* as for ZZ.

   3.a) Neglect third generation except for diagrams that involve Z and γ^*.

   3.b) We expect accuracy $\approx \mathcal{O}(10\%)$. At LO we find

$$\sigma^{3gen}_{gg\to W^+W^-}/\sigma^{2gen}_{gg\to W^+W^-} \approx 1.1$$

constant with collision energy[3] and with kinematical cuts fiducial x-section.

[3] 8 TeV or 13 TeV !

The case of $g\, g \to W^+ W^- \to e^- \nu_e\, \mu^+ \bar{\nu}_\mu$

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Also in this case **large radiative corrections**

- @ 8 TeV

$$\sigma_{\mathrm{LO}}^{gg\to WW} = 20.9^{+6.8}_{-4.8}\ \mathrm{fb}, \quad \sigma_{\mathrm{NLO}}^{gg\to WW} = 32.2^{+2.3}_{-3.1}\ \mathrm{fb},$$

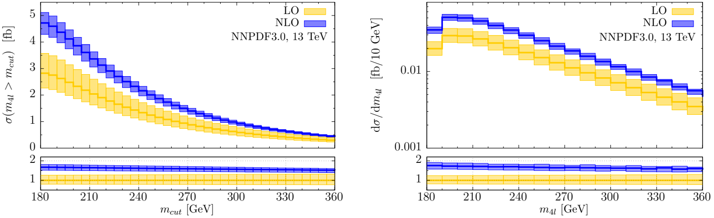
- @ 13 TeV

$$\sigma_{\mathrm{LO}}^{gg\to WW} = 56.5^{+15.4}_{-11.5}\ \mathrm{fb}, \quad \sigma_{\mathrm{NLO}}^{gg\to WW} = 79.5^{+4.2}_{-5.9}\ \mathrm{fb}.$$

We find an increase of $\mathcal{O}(30\% - 80\%)$ @ 8 TeV
and an increase of $\mathcal{O}(20\% - 60\%)$ @ 13 TeV

Note that here **different central scale**, upper value is $\mu = m_W/2$, lower value is $\mu = 2m_W$! Results comparable to ZZ when correcting for different scale!

Of course we can go differential - **kinematic distributions** @ 13 TeV



Up, left: cumulative cross section for $gg \to (Z/\gamma)(Z/\gamma) \to e^+e^-\mu^+\mu^-$ as a function of the lower cut on four-lepton invariant mass.

Up, right: distribution of the invariant mass of the four leptons.

Lower panes show ratios of the LO (yellow) and NLO (blue) distributions evaluated at three different scales to the LO distribution evaluated at $\mu = 2m_Z$.

What can we learn from this?

Interesting implications for **NNLO** corrections to $pp \to ZZ$ @ 8 TeV

$$\text{At } \mu = {m_Z}^{4} \quad \left.\begin{array}{cc} - & \text{NNLO in } q\bar{q} \to ZZ \\ - & \text{LO in } gg \to ZZ \end{array}\right\} \approx 12\% \text{ of total cross section}$$

$gg \to ZZ$ @ LO provides $\approx 60\%$ of NNLO corrections, i.e. $\approx 7\%$

How does this influence the theoretical uncertainty of the NNLO computation?

[4] with NNLO pdfs!

NNLO corrections to $pp \to ZZ$ @ **8 TeV** computed

a) at scale $\mu = m_Z \to$ increases the cross section

b) with NNLO pdfs $\to$ lowers the cross section

Using same set-up we find that $gg \to ZZ$ @LO should be increased of $\approx 80\%$!

$\Downarrow$

This implies that NNLO corrections should be increased from 12% to $\approx 18\%$!

This is beyond the $\mathcal{O}(3\%)$ scale uncertainty!

Similar conclusions at **13 TeV** $\to$ we find 16% would increase to $\approx 23\%$!

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What are now implications for **NNLO** corrections to $pp \to WW$?

$$\text{At } \mu = m_W \quad \left.\begin{array}{cc} - & \text{NNLO in } q\bar{q} \to WW \\ - & \text{LO in } gg \to WW \end{array}\right\} \approx 9 - 12\% \text{ of total cross section}$$

$gg \to WW$ @ LO provides now only $\approx 35\%$ of NNLO corrections, i.e. $\approx 3 - 4\%$

This implies that taking NLO $gg \to WW$ into account shifts **NNLO** predictions of about $\approx \mathcal{O}(2\%)$ $\to$ **comparable** to NNLO scale uncertainty!

Finally, shift much larger than contribution $gg \to H^* \to WW \to 2l\,2\nu \approx 1\text{fb}$

We study also cross section in the **fiducial volume**. ATLAS cuts are [Monni, Zanderighi '14]

8 TeV fiducial region
$p_t > 25(20)$ GeV for the leading (subleading) lepton and charged leptons separated by $\Delta R > 0.1$
muon pseudorapidity $\lvert y\rvert < 2.4$ and electron pseudorapidity $\lvert y\rvert < 1.37$ or $1.52 < \lvert y\rvert < 2.47$
no jets (anti-k_t, $R = 0.4$) with $p_t > 25$ GeV and $\lvert y\rvert < 4.5$ separated from the electron by $\Delta R > 0.3$
$m_{ll'} > 15, 15, 10$ GeV and $\lvert m_{ll'} - m_Z\rvert > 15, 15, 0$ GeV for ee, $\mu\mu$, and $e\mu$, respectively
$p_{t,\mathrm{Rel}}^{\nu+\bar{\nu}} > 45, 45, 15$ GeV and $p_t^{\nu+\bar{\nu}} > 45, 45, 20$ GeV for ee, $\mu\mu$, and $e\mu$, respectively

A lesson to learn

Implementing ATLAS cuts we find

	$\sigma_{\mu\mu,8\ \mathrm{TeV}}$	$\sigma_{ee,8\ \mathrm{TeV}}$	$\sigma_{e\mu,8\ \mathrm{TeV}}$
$\sigma_{gg,\mathrm{LO}}$ [fb]	$5.94^{+1.89}_{-1.35}$	$5.40^{+1.71}_{-1.23}$	$9.79^{+3.13}_{-2.24}$
$\sigma_{gg,\mathrm{NLO}}$ [fb]	$7.01^{-0.36}_{-0.17}$	$6.40^{-0.32}_{-0.16}$	$11.78^{-0.46}_{-0.34}$

LO and NLO gluon-initiated fiducial cross sections for in the ee, $\mu\mu$, and $e\mu$ decay channels. For **central scale** NLO increases results of $\approx 18-20\%$.

This is **substantially smaller** than inclusive x-section, mainly due to p_T veto on jets for $p_T > 25$ GeV which suppresses hard gluons emissions. See $gg \to H$.

CONCLUSIONS

- *VV* production is of crucial importance for LHC phenomenology in and beyond the SM

- Computation of *NLO* corrections to *gg* channel fundamental for correct estimate of theory uncertainty!

- Radiative corrections in **fiducial volume** can be very different

$$\Downarrow$$

Much attention has to be put in extrapolation fiducial $\rightarrow$ inclusive and comparison theory-experiment!