W^+W^- + dijet to next-to-leading order in QCD

Raoul Röntsch

Rudolf Peierls Centre for Theoretical Physics, University of Oxford

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With Tom Melia, Kirill Melnikov, Giulia Zanderighi
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Motivation

Phenomenological - background to Higgs:

- Around 10% of Higgs bosons produced by gluon fusion at Tevatron in association with two jets (*Anastasiou, Dissertori, Grazzini, Stöckl, Webber, hep-ph:0905.3529; Campbell, Ellis, Williams, hep-ph:1001.4495*)
- Leading background to Higgs produced by WBF

Theoretical - frontier of computations:

- $pp \to W^+W^-jj$ is a $2 \to 4$ process - theoretically challenging for NLO QCD as number of Feynman diagrams increases faster than $N!$.
- Use D-dimensional unitarity (*Bern, Dixon, Kosower; Britto, Cachazo, Feng; Ellis, Giele, Kunszt, Melnikov*) and Ossola-Papadopoulos-Pittau reduction to simplify the calculation of the virtual amplitude.
- These (and other) methods have allowed many $2 \to 4$ processes to be calculated. $pp \to W(Z,\gamma) + 3$ jets, $pp \to t\bar{t}b\bar{b}$, $pp \to b\bar{b}b\bar{b}$, $pp \to t\bar{t} + 2$ jets, $pp \to t\bar{t} \to W^+W^-b\bar{b}$, $pp \to W^+W^+ + 2$ jets.
- Complications (related to presence of two colourless particles) arise when applying these methods to W^+W^-jj process, due to use of colour ordering.

Brief summary of method

- Virtual amplitudes stripped of colour factors to give partial amplitudes $\rightarrow$ primitive amplitudes.
- OPP subtraction: tensor integrals in primitive amplitude written in terms of **scalar integrals** (known) and **coefficients.**
- Analytical form of coefficients in loop momentum known from OPP.
- By choosing (complex) momenta such that propagators vanish, can solve for coefficients.
- Equivalent to performing a unitarity cut on the primitive amplitudes, resulting in tree-level helicity amplitudes.
- $\rightarrow$ computed with Berends-Giele recursion relations (also used to calculate Born amplitudes and real emission corrections).

Checks

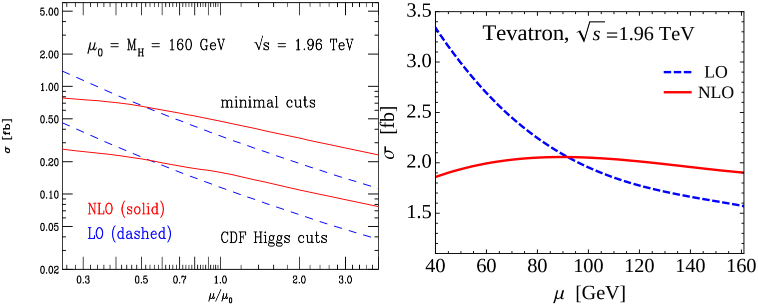
- **Tree level**: Born and real amplitudes (all flavour combinations, all initial state partons), as well as Born cross-section, checked against MadGraph.
- **Gauge invariance**: checked for all amplitudes for both gluons and W bosons.
- **Virtual**: Poles reproduced correctly. Full one-loop amplitude checked against independent program which uses OPP but not unitarity cuts.
- **Catani-Seymour dipoles**: Soft and collinear limits checked, virtual poles cancel with integrated dipoles, cross-section independent of α-parameter.

Parameters for Tevatron

Cuts used similar to those of CDF in Higgs searches:

- Jets defined using $k_\perp$-algorithm with $\Delta R_{j_1 j_2} > 0.4$.
- Jet cuts: $p_{\perp,j} > 15$ GeV and $|\eta_j| < 2.5$
- Lepton cuts: $p_{\perp,l_1} > 20$ GeV, $|\eta_{l_1}| < 0.8$; $p_{\perp,l_2} > 10$ GeV, $|\eta_{l_2}| < 1.1$.
- Lepton isolation: jets within $\Delta R = 0.4$ of a lepton must have $p_\perp < 0.1 p_{\perp,l}$.
- Lepton cuts: $m_{l_1 l_2} > 16$ GeV and $\not{E}_\perp^{\text{spec}} = \not{E}_\perp \sin\left[\min(\Delta\phi, \frac{\pi}{2})\right] > 25$ GeV.

Tevatron Results



Left plot from Campbell, Ellis and Williams, hep-ph:1001.4495

We find $\sigma_{\rm LO} = 2.5 \pm 0.9$ fb, $\sigma_{\rm NLO} = 2.0 \pm 0.1$ fb.

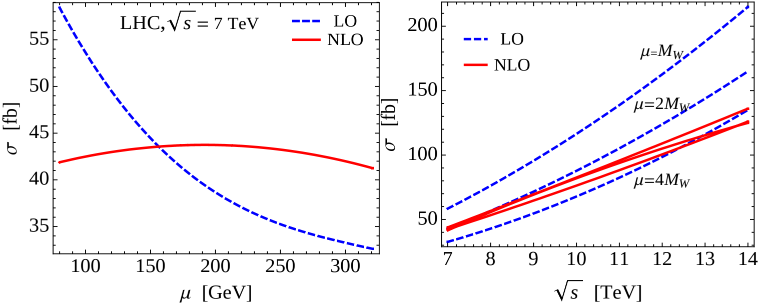
At LO, **uncertainty** in background is about four times larger than **signal!**

Even at NLO, uncertainty in background is close to signal.

LHC Parameters

- Centre-of-mass energy $\sqrt{s} = 7$ TeV.
- Jets defined using anti-$k_\perp$ algorithm with $\Delta R > 0.4$
- Jet cuts: $p_{\perp,j} > 30$ GeV and $|\eta_j| < 3.2$
- Lepton cuts: $p_{\perp,l} > 20$ GeV, $|\eta_l| < 2.4$, $p_{\perp,\mathrm{miss}} > 30$ GeV.

LHC results



$\sigma_{\rm LO} = 46 \pm 13$ fb, $\sigma_{\rm NLO} = 42 \pm 1$ fb.

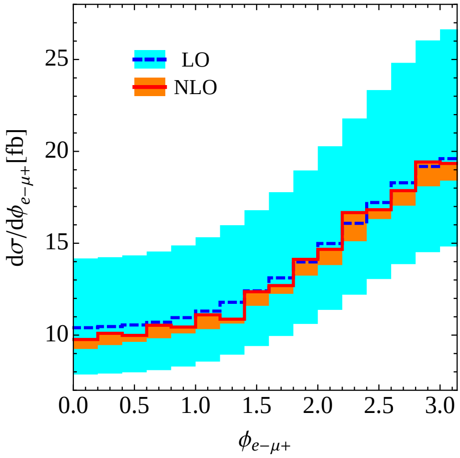
A few such events may have already been recorded.

At NLO, approximately linear increase in cross-section as $\sqrt{s}$ is increased.

"Optimal" factorization/renormalization scale: around $2M_W$ at $\sqrt{s} = 7$ TeV, $4M_W$ at $\sqrt{s} = 14$ TeV.

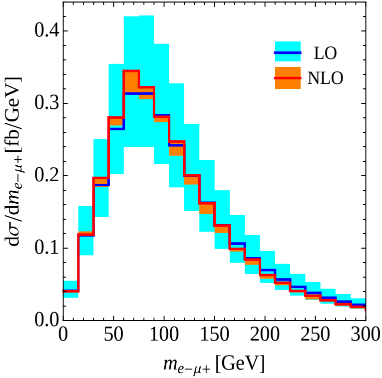
LHC results

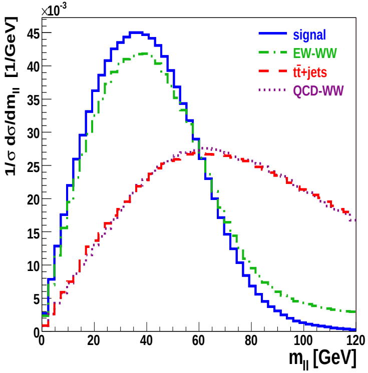
To discriminate between signal and background: distributions.
Useful distributions: opening angles between leptons $\phi_{e^-\mu^+}$.
Higgs: small angle; background: back-to-back



LHC results

Lepton mass $m_{ll} = 2E_{l_1}E_{l_2}(1 - \cos\phi_{ll})$.

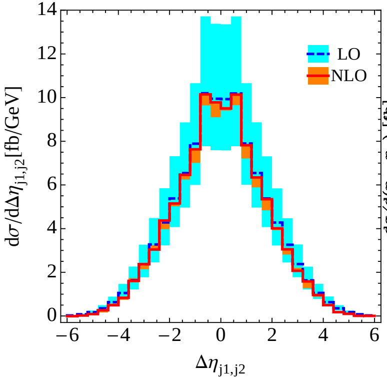


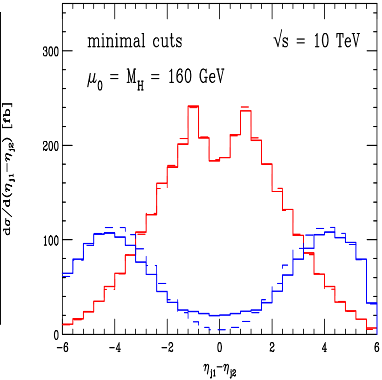


Right plot taken from Klämke and Zeppenfeld, hep-ph:0703202

LHC results

Also: difference in rapidity of the two hardest jets $\Delta\eta_{j_1 j_2}$.
This is different for Higgs produced via WBF and gluon fusion.

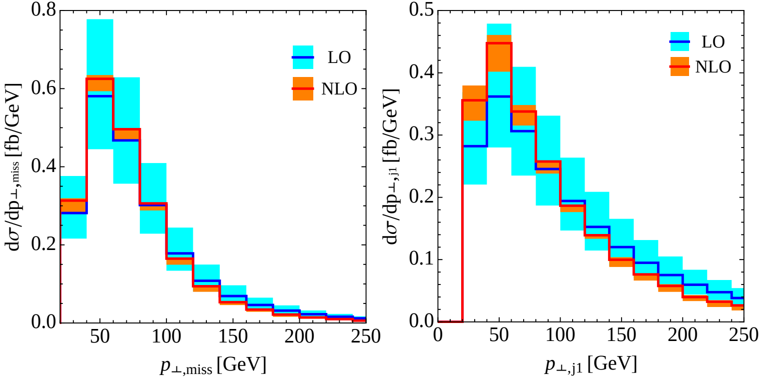




Right plot taken from Campbell, Ellis and Williams, hep-ph:1001.4495

NLO results greatly reduce scale uncertainty → improved reliability.

LHC results



No changes in shape (although mild softening at high $p_\perp$).

Reduced scale uncertainty.

Conclusions

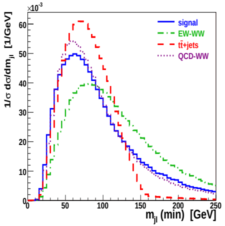
- We have used generalised unitarity and the OPP subtraction method to calculate the process $pp \to W^+W^-jj$ to NLO QCD.
- NLO corrections reduce the scale uncertainty, and are important when viewing this process as a background to e.g. Higgs production in association with two jets.
- NLO corrections allow more accurate calculations of distributions $\to$ discriminate between Higgs production and this background.

Backup slides

Top background

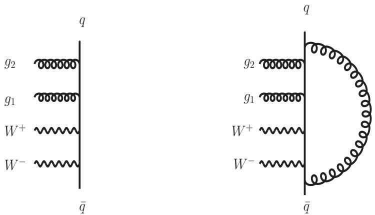
From Klämke and Zeppenfeld, hep-ph:0703202

cuts	GF	EW $WWjj$	$t\bar{t}$	$t\bar{t}j$	$t\bar{t}jj$	QCD $WWjj$	S/B	$S/\sqrt{B}$
inclusive cuts	115.2	75.1	6832	9518	1676	363	1/160	4.6
$+$ b veto	99.2	67.4	833	1822	564	307	1/36	9.1
$+$ $R_{\ell\ell}$, $m_{\ell\ell}$ cut	55.8	30.7	104	218	86.4	42.7	1/8.6	13.9
$+$ $p_{T\ell}$ cut	41.5	22.3	38.3	87.7	29.2	20.5	1/4.8	16.2
$+$ m_T^{WW} cuts	37.1	19.9	30.1	63.4	19.3	13.4	1/3.8	16.8
$+$ p_T cut	31.5	16.5	23.3	51.1	11.2	11.4	1/3.6	16.2

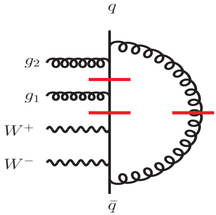


WW pair, quark pair and gluon pair

Two partonic processes: $0 \to \bar{q}_1 q_2 g g W^+ W^-$ and $0 \to \bar{q}_1 q_2 \bar{q}_3 q_4 W^+ W^-$.
First is straightforward:

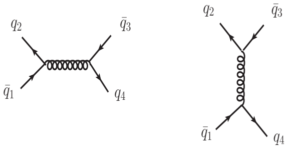


(with additional 7 primitive amplitudes).
E.g. of unitarity cut:

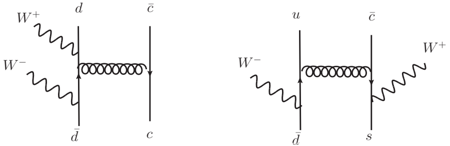


WW pair and two quark pairs

This is a little more complicated: depending on flavours and emission of W-bosons, can either have $[\bar{q}_1 q_2], [\bar{q}_3 q_4]$ or $[\bar{q}_1 q_4], [\bar{q}_3 q_2]$:



Additionally, W-bosons may both be emitted off same line, or off separate lines:



(need to keep track of flavour and helicity...)
These are minor complications which can be handled without serious trouble.

Parameters

- W bosons produced on-shell and decay leptonically $W^+W^- \to \nu_\mu \mu^+ e^- \bar{\nu}_e$.
- $M_W = 80.419$ GeV, $\Gamma_W = 2.141$ GeV and $\Gamma_Z = 2.49$ GeV.
- $\alpha(M_Z) = 1/128.802$, $\sin^2\theta_W = 0.2222$.
- MSTW08LO and MSTW08NLO used, corresponding to $\alpha_s(M_Z) = 0.13939$ and $\alpha_s(M_Z) = 0.12018$.