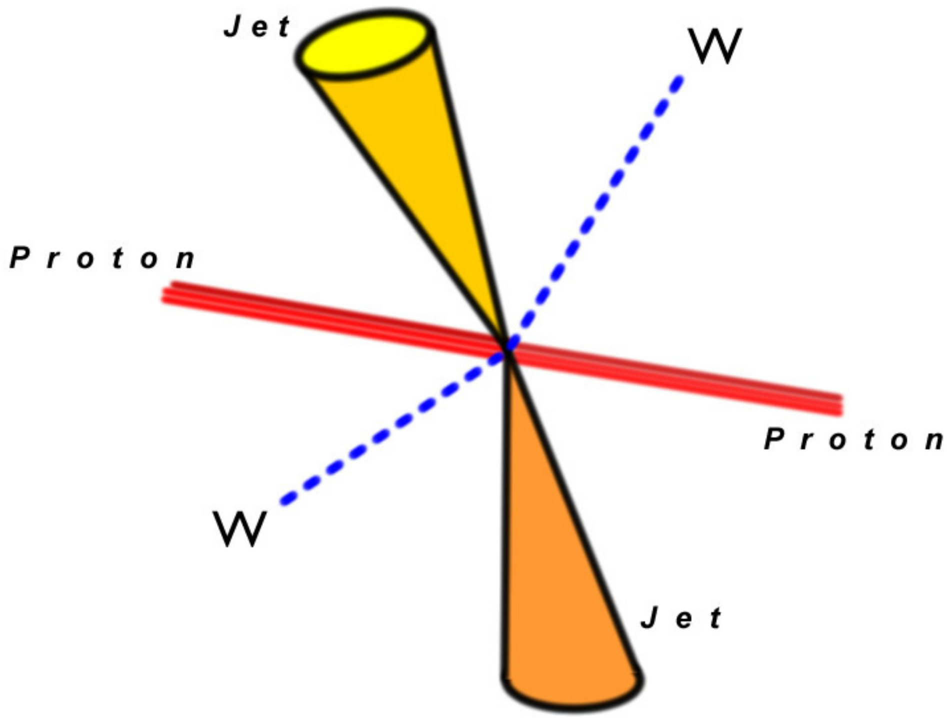
Weak Bosons and Jets at the LHC

Tom Melia, RADCOR Sep 2011



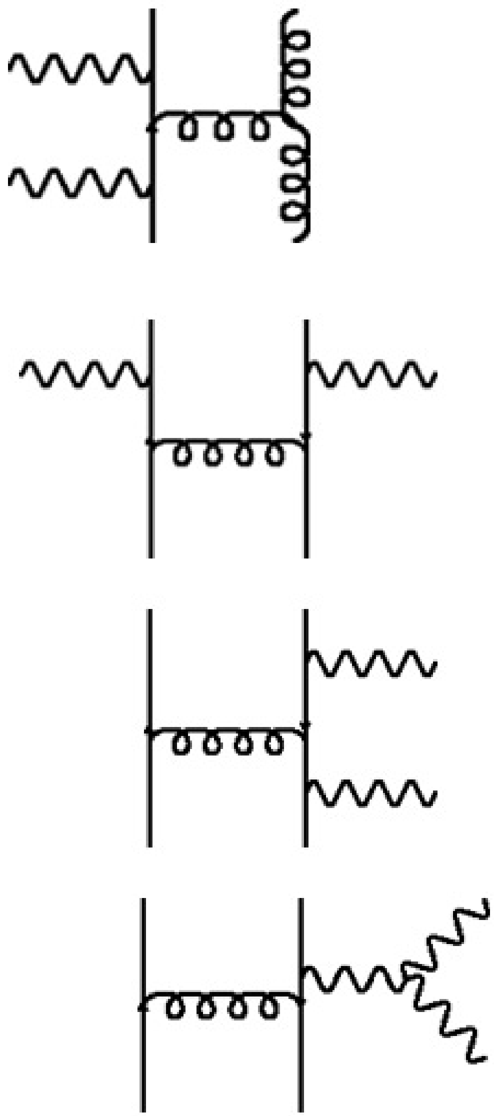
Work with Raoul Rontsch, Kirill Melnikov, Paolo Nason and Giulia Zanderighi

W^+W^+jj: **JHEP 1012 053 / arXiv:1007.5313**
W^+W^-jj: **Phys. Rev. D 83, 114043 / arXiv:1104.2327**
`POWHEG BOX`: **Eur. Phys. J. C 71 1670 / arXiv:1102.4846**

Oxford Theoretical Physics

Types of Feynman Diagram

(even though we do not evaluate
any Feynman diagram)



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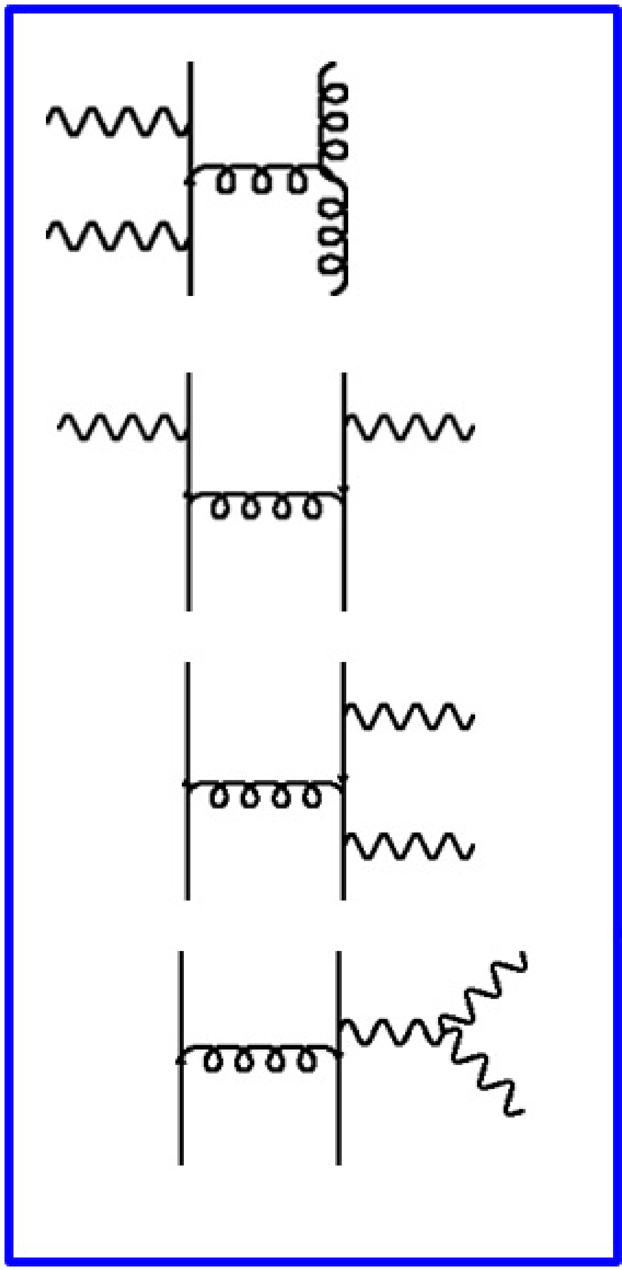

$W^+W^-j\ j$

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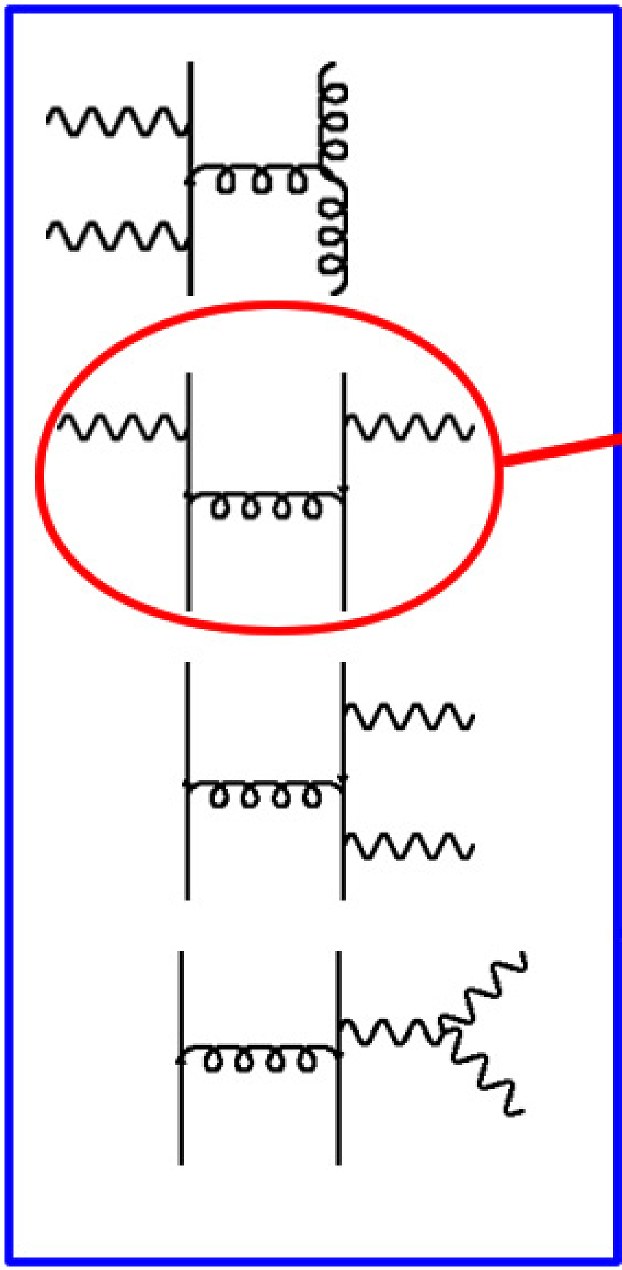

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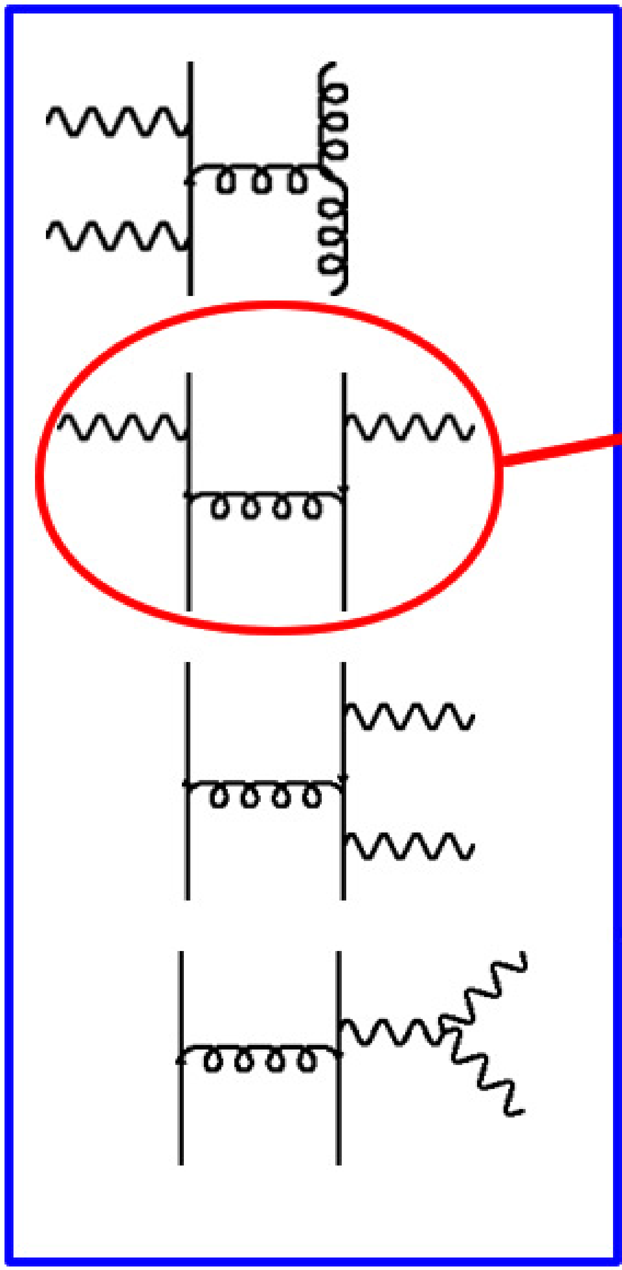


W^+W^+jj

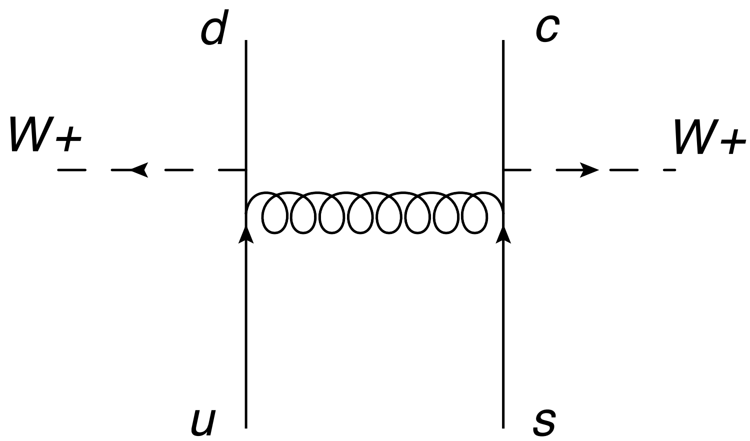
- NLO QCD Corrections
- Implementation in the POWHEG BOX

W^+W^-jj

- NLO QCD Corrections

W^+W^+jj at the LHC

- Interesting process both theoretically and experimentally.



- Need W-bosons on separate quark lines. This means cross-section is infra-red safe as the jet p_T go to zero.

- We consider the leptonic decay of both W-bosons as this is a clean signature and shows up the double positive sign.

- Cross-section for this decay is around 6fb at 14TeV (l^-l^- is 40% of the size).

W^+W^+jj at the LHC

- Exotic SM signal!

And a background process to

- Double parton scattering

  e.g. J. R. Gaunt, C. H. Kom, A. Kulesza and W. J. Stirling, hep-ph/1003.3953

- R-parity violating smuon production

  e.g. H. K. Dreiner, S. Grab, M. Kramer and M. K. Trenkel, Phys. Rev. D75 (2007)

- Doubly charged Higgs production

  e.g. J. Maalampi and N. Romanenko, Phys. Lett. B 532, 202 (2002)

- Di-quark production

  e.g. T. Han, I. Lewis and T. McElmurry, JHEP 1001, 123 (2010)

W^+W^-jj at the LHC

- 2005 Les Houches Wishlist process.
- Background to Higgs boson production.
- 10% of Higgs bosons produced at the LHC are in association with two jets
  e.g. Campbell, Ellis, Zanderighi (2006); Anastasiou, Dissertori, Grazzini, Stockli, Webber (2009).
- W^+W^-jj is the dominant irreducible background if the Higgs is produced by Weak Boson Fusion. Signature of this event involves two forward tagging jets.
- Background to a classic BSM search - two leptons, jets, missing energy.

Theoretical incentives to calculate NLO QCD corrections to both processes

- NLO QCD for > 5 particles is difficult. For the virtual amplitude, the number of Feynman diagrams grows as $N!$.

- On-shell methods as currently formulated require working with an ordering of external lines - colour-ordered/primitive amplitudes. Having two colourless bosons considerably complicates things.

- The number of $2 \longrightarrow 4$ processes known at NLO is growing!
  $pp \longrightarrow Vjjj$, Berger et al. (2009); Ellis, Melnikov, Zanderighi (2009).
  $pp \longrightarrow t\bar{t}b\bar{b}$, Brendenstein, Denner, Dittmaier, Pozzorini (2009); Bevilacqua et. al. (2010).
  $pp \longrightarrow t\bar{t}jj$, Bevilacqua, Czakon, Papadopoulos, Worek (2010).
  $pp \longrightarrow b\bar{b}b\bar{b}$, Binoth et. al. (2010).
  $pp \longrightarrow W^+W^-b\bar{b}$, Bevilacqua et. al. (2010); Denner, Dittmaier, Kallweit, Pozzorini (2010).
  $2 \longrightarrow 5$ process: $pp \longrightarrow Wjjjj$. Binoth et. al. (2010).

- Platform for automation of NLO processes being developed:
  SAMURAI, MC@NLO.

Method of Calculation

In the past three years, methods of D-dimensional unitarity *(Bern, Dixon, Kosower; Cachazo, Britto, Feng; Ellis, Kunszt, Giele, Melnikov and more)* along with Ossola-Papadopoulos-Pittau (OPP) reduction have simplified the calculation of the virtual amplitude enormously.

Unitarity method: We write the amplitude

$$\mathcal{A}_N(p_1,\ldots,p_N) = \sum_{1\le i_1<i_2<i_3<i_4\le N} d_{i_1i_2i_3i_4} I_{i_1i_2i_3i_4} + \sum_{1\le i_1<i_2<i_3\le N} c_{i_1i_2i_3} I_{i_1i_2i_3} + \sum_{1\le i_1<i_2\le N} b_{i_1i_2} I_{i_1i_2} + \sum_{1\le i_1\le N} a_{i_1} I_{i_1}$$

where

$$I_{i_1\ldots i_k} = \int \frac{[dl]}{D_1 \ldots D_k} \quad , \qquad D_i = (l + \sum_{j=1}^{i} p_j)^2 - m^2.$$

To find the coefficients $d_{i_1i_2i_3i_4} \ldots a_{i_1}$, we can write the 1-loop amplitude as

$$\mathcal{A}_N(p_1, \ldots, p_N) = \int [dl] \frac{N(p_i; l)}{D_1 \ldots D_N}$$

and the numerator

$$\begin{aligned} N(p_i; l) &= \sum_{1 \le i_1 < i_2 < i_3 < i_4 \le N} \left(d_{i_1i_2i_3i_4} + \tilde{d}_{i_1i_2i_3i_4}(l) \right) \prod_{i \ne i_1i_2i_3i_4} D_i \\ &+ \sum_{1 \le i_1 < i_2 < i_3 \le N} (c_{i_1i_2i_3} + \tilde{c}_{i_1i_2i_3}(l)) \prod_{i \ne i_1i_2i_3} D_i \\ &+ \sum_{1 \le i_1 < i_2 \le N} \left(b_{i_1i_2} + \tilde{b}_{i_1i_2}(l) \right) \prod_{i \ne i_1i_2} D_i \\ &+ \sum_{1 \le i_1 \le N} (a_{i_1} + \tilde{a}_{i_1}(l)) \prod_{i \ne i_1} D_i \end{aligned} \tag{1}$$

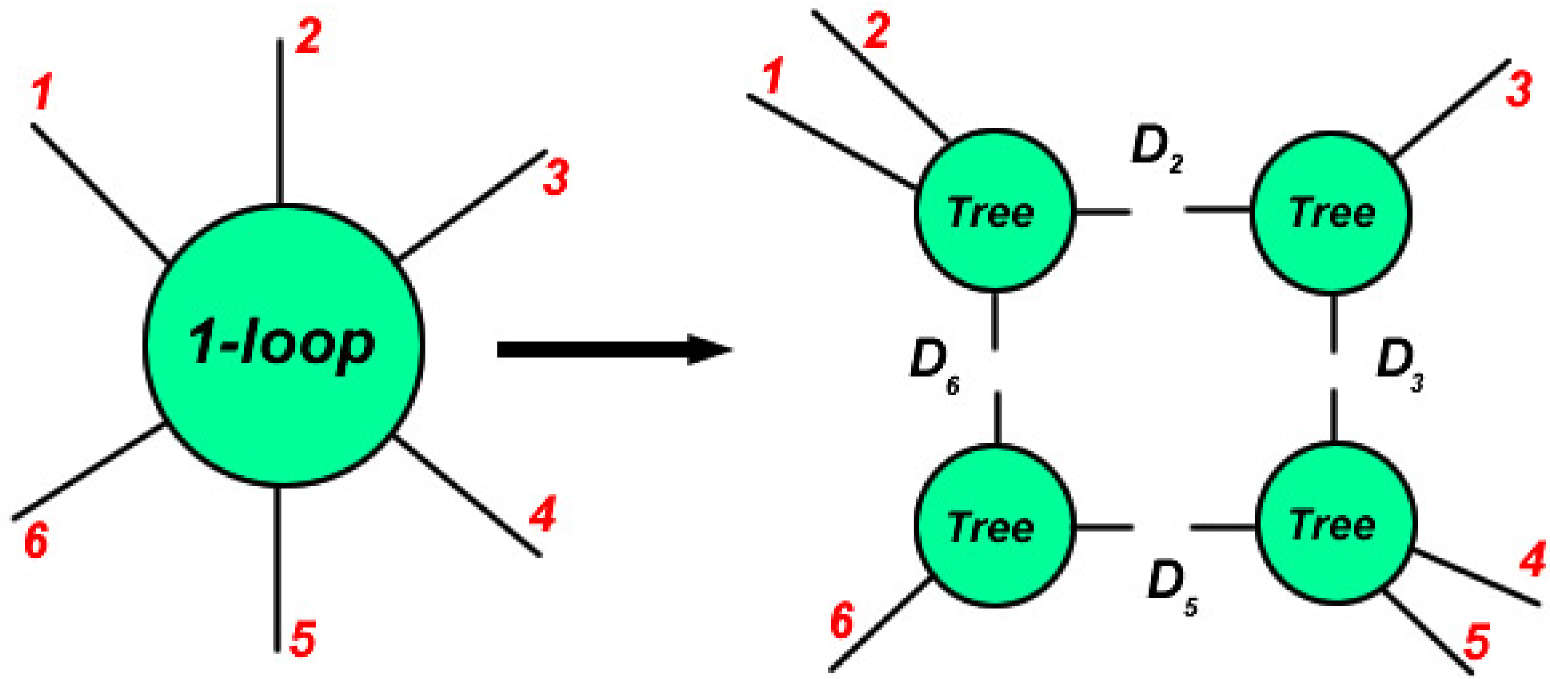
where the tilde terms vanish upon integration over l.

OPP tells us the analytical form in l of the coefficients.

For example, to find the coefficient $\bar{d}_{2356}(l) = d_{2356} + \tilde{d}_{2356}(l)$, look for $l = \hat{l}$ so that $D_2 = D_3 = D_5 = D_6 = 0$. Then eqn (1) becomes

$$N(p, \hat{l}) = \bar{d}_{2356}(\hat{l}) \prod_{i \neq 2,3,5,6} D_i(\hat{l}).$$

What is more, the 1-loop amplitude factorises at this point:



so $\bar{d}_{2356} = A_{12}^{tree} \times A_3^{tree} \times A_{45}^{tree} \times A_6^{tree}$.

Amplitudes calculated with Berends-Giele recursion relations.

Repeat this process to find all coefficients and therefore the full amplitude (...almost).

- Analytically (using dim.reg.) one finds 'rational' terms from parts of the coefficients which are $\mathcal{O}(\epsilon)$ hitting UV poles which are $\mathcal{O}(1/\epsilon)$.

- But we want to do this numerically: we can't work to $\mathcal{O}(\epsilon)$.

- So we do this with loop momentum in $D = 5$ dimensions and the internal particles' spin in both $D_s = 6$ and $D_s = 8$ dimensions.

- The extra-dimensional part of l enters into the analytical form of $\tilde{d}(l) \ldots \tilde{a}(l)$ as (coeff.) $\times$ $\mathrm{l}^2_{\mathrm{XD}}$ or (coeff.) $\times$ $(\mathrm{l}^2_{\mathrm{XD}})^2$.

- We pick up the rational terms from the new integrals involving extra-dimensional parts of l, such as

$$\int [dl] \frac{l^2_{\mathrm{XD}}}{D_1 D_2 D_3 D_4}$$

- The amplitude is essentially *linear* in D_s. Extrapolate back to e.g. $D_s = 4$ or $D_s = 4 - 2\epsilon$ (FDH Scheme, 't H-V scheme).

Checks

- **Tree level:** Born, real and cross-section checked with MG/ME.

- **Virtual:** Poles reproduced correctly. In addition we cross-check the *full* 1-loop amplitude at individual phase-space points with an independent Feynman-diagram based program.

- **Catani-Seymour dipoles:** - Collinear limits - Cancellation of virtual poles with integrated dipoles - Independence of cross-section on α parameter.

Results for W^+W^+jj

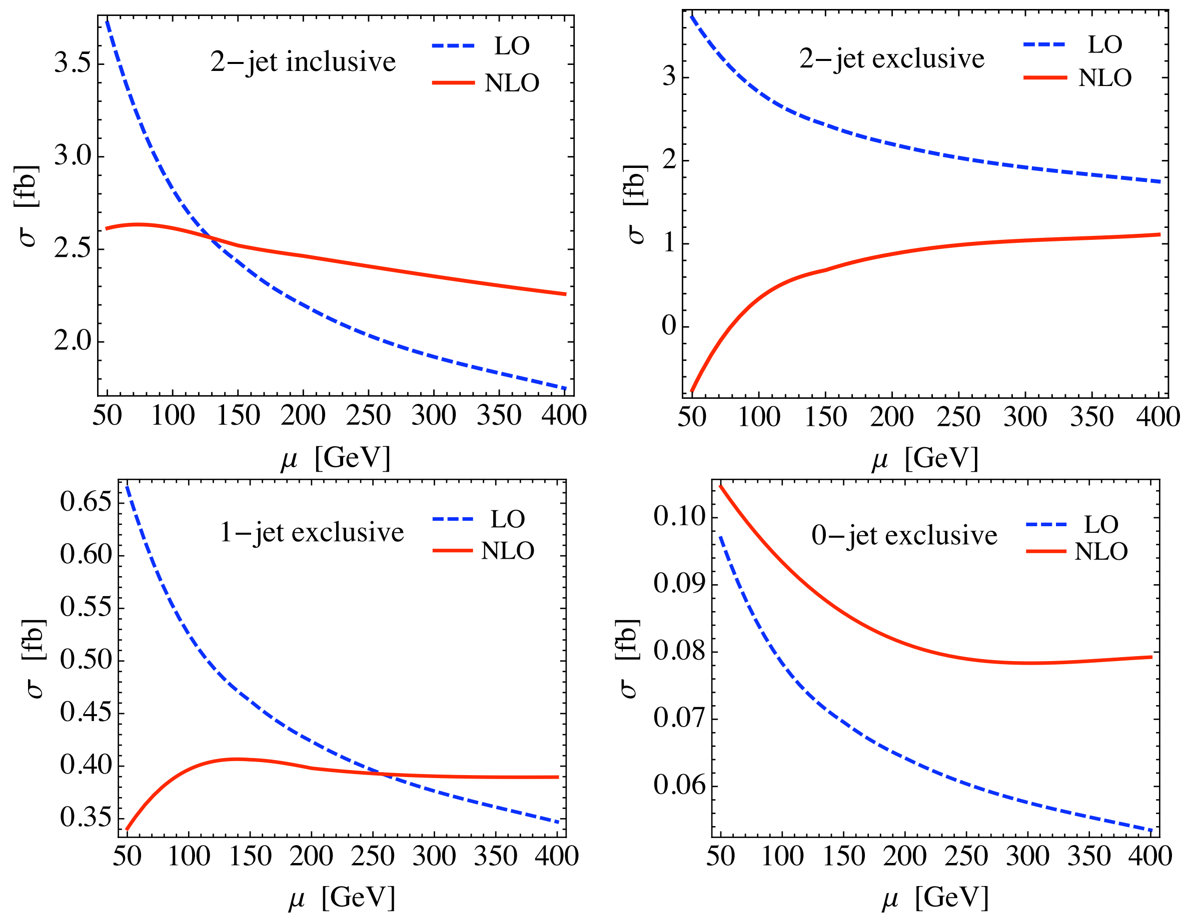
Cuts and Input Parameters:

pp collisions with $\sqrt{s}$ =14TeV
Allow W-bosons to decay leptonically into $e^+\mu^+$
(full l^+l^+ is a factor of 2 greater)

- Jets are reconstructed with anti-k_T algorithm with $R = 0.4$.
- Jet cuts: $p_{T,j}$ >30GeV.
- Lepton cuts: $p_{T,j}$ >20GeV, $|\eta_l|$ <2.4.
- Missing transverse momentum cut: $p_{T,miss}$ >30GeV.

- MSTW08LO and MSTW08NLO parton distributions.
- $\alpha_s(M_Z) = 0.13939$ and 0.12018 respectively.
- α_{QED}=1/128.802, $\sin^2\theta_W$=0.2222.
- M_W=80.419 GeV, Γ_W=2.141 GeV, Γ_Z=2.490 GeV.

W^+W^+jj Cross-sections and μ dependence



$\mu = \mu_R = \mu_F$.

NLO cross section dependence on μ reduced significantly compared to LO.

σ^{LO} =2.7±1.0 fb, σ^{NLO} =2.44±0.18 fb (∼60 l^+l^+ events for 10 fb^{-1})

Notably larger cross section for 2-jet inclusive than for 2-jet exclusive
→ presence of a relatively hard third jet in quite a large fraction of events.

Implementation of W^+W^+jj in the POWHEG BOX

- Benefits of a NLO calculation together with a parton shower.
- POWHEG BOX interface - supply a few ingredients:
  — Phase space
  — Flavour information
  — Born, real and virtual matrix elements.

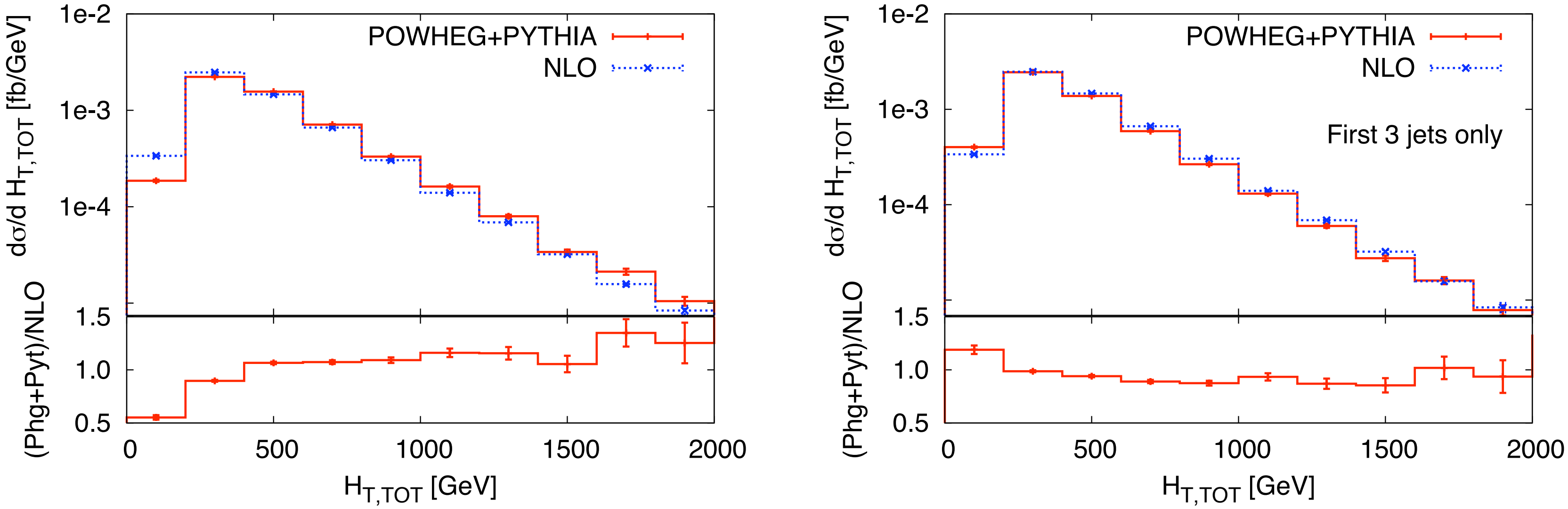
- No generation cut complications arise because there are no soft or collinear divergences at Born level.
- W^+W^+jj is the first $2 \longrightarrow 4$ process to be implemented in NLO+PS framework.
- POWHEG implementation framework for arbitrary processes exists, but the virtual corrections here are computationally demanding - technical modifications allowed for parallel running.

Selected POWHEG W^+W^+jj Results

— Here we consider pp collisions at $\sqrt{s} = 7$ TeV. No jet cuts are applied. —

With the previous leptonic cuts, $\mu_R = \mu_F = (p_{t,1} + p_{t,2} + E_{t,W_1} + E_{t,W_2})/2$

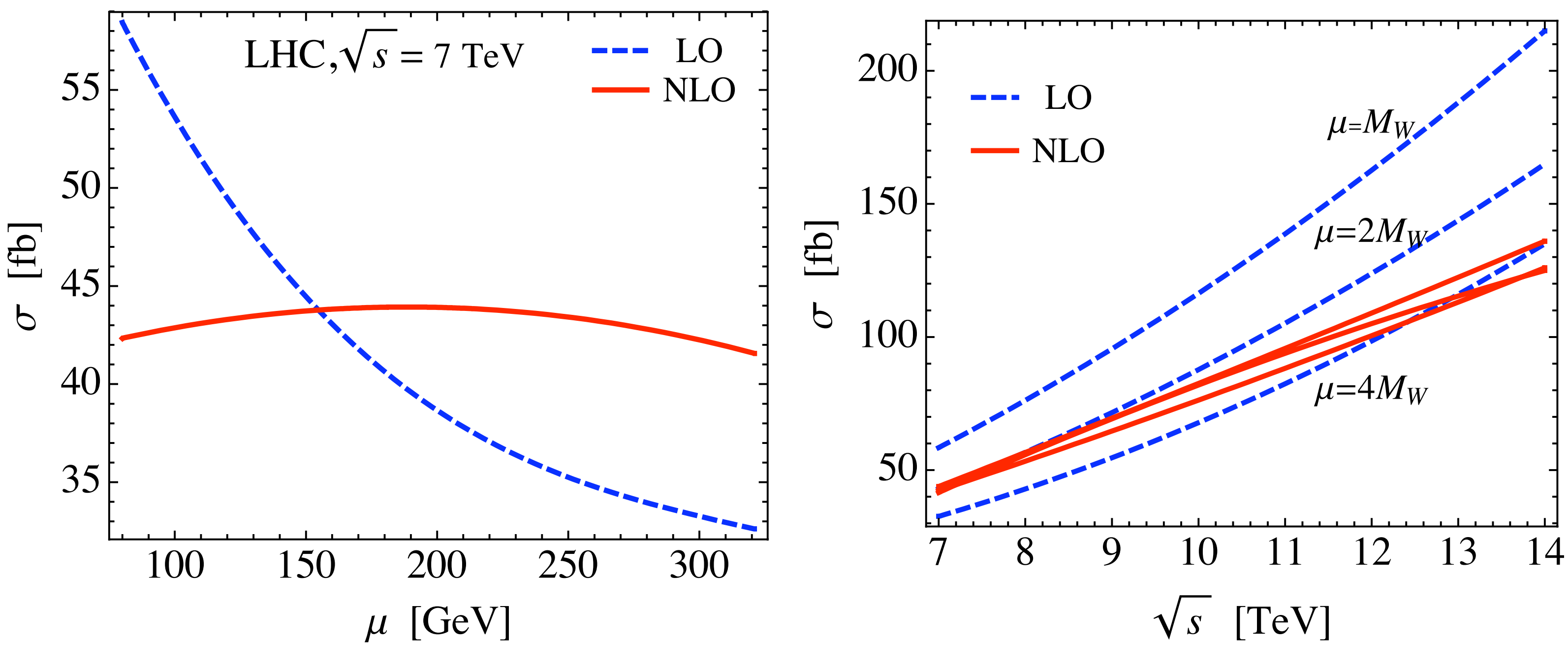
$$\sigma_{NLO} = 1.11 \pm 0.01_{(stat)} \text{ fb}$$
$$\sigma_{PYT} = 1.06 \pm 0.01_{(stat)} \text{ fb}$$



- Most kinematic distributions show minor shape change after parton showering.
- $H_{T,TOT} = p_{t,e^+} + p_{t,\mu^+} + p_{t,miss} + \sum_j p_{t,j}$ is affected by soft partons and underlying event **PYTHIA** adds (no jet cut!).
- Causes a migration of the NLO distributed events to higher $H_{T,TOT}$ bins.

Results for W^+W^-jj

- Allow W-bosons to decay leptonically into $e^+\mu^-$ (full $l^+l'^- \times 4$) and with the same leptonic cuts and EW parameters as previously described.
- Jet cuts: $p_{T,j}$ >30GeV, $|\eta_j| < 3.2$.



$\mu = \mu_R = \mu_F$.

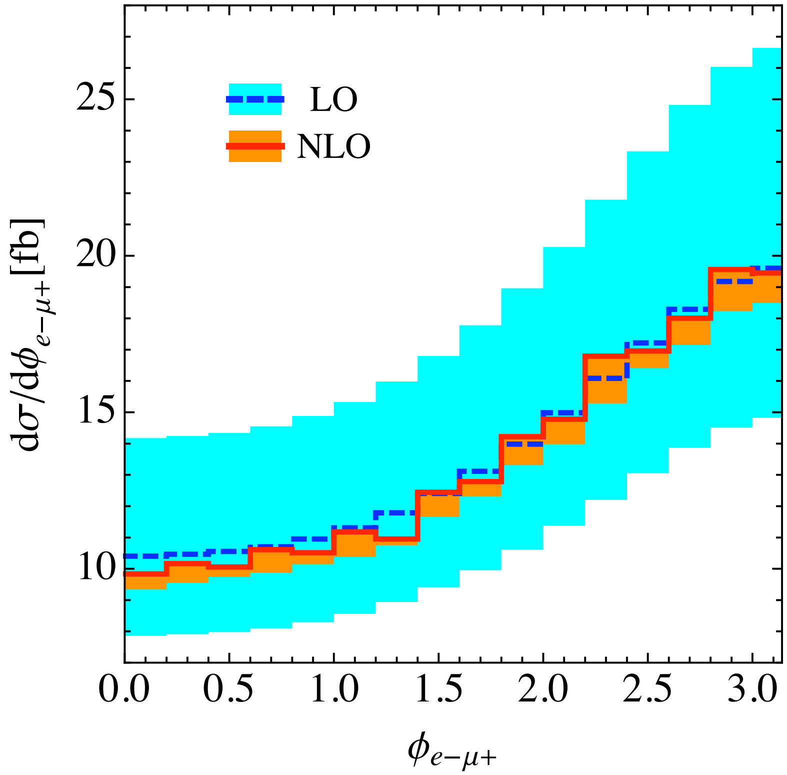
- Dramatic reduction in scale dependence in going to NLO.

$$\sigma_{LO} = 46 \pm 13 \text{ fb} \qquad \sigma_{NLO} = 42 \pm 1 \text{ fb}$$

- Optimal scale choice changes from $2M_W$ at 7 TeV to $4M_W$ at 14 TeV.

Kinematic distributions for W^+W^-jj

Selected distributions relevant for Higgs searches at 7 TeV:

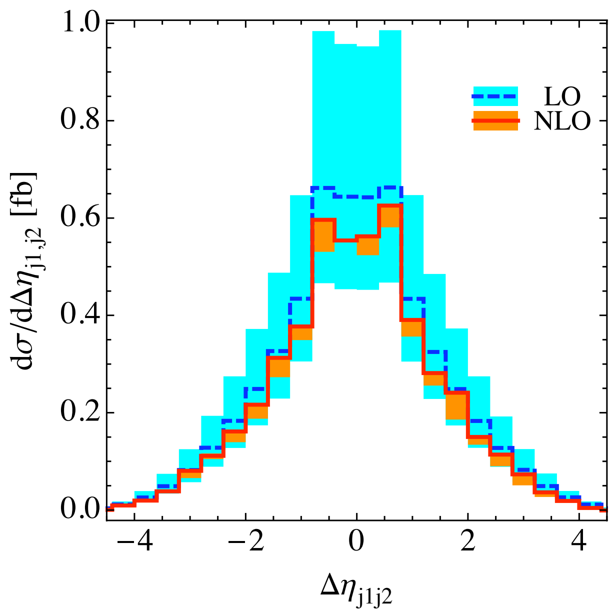


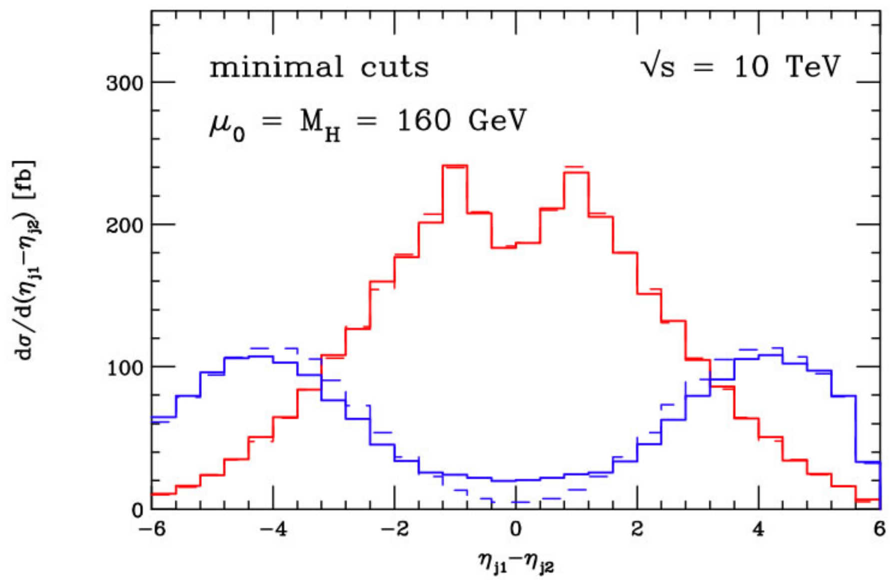
$\mu = \mu_R = \mu_F$. Solid line $\mu = 2M_W$, variation $M_W < \mu < 4M_W$.

- Opening angle of the leptons. For $H \to WW \to e\mu\nu\nu$ the leptons have small opening angle. Here they prefer to be back-to-back.
- Large reduction in the theoretical uncertainties of the distribution. No observed shape change.

Kinematic distributions for W^+W^-jj

Selected distributions relevant for Higgs searches at 7 TeV:





$\mu = \mu_R = \mu_F$. Solid line $\mu = 2M_W$, variation $M_W < \mu < 4M_W$.

- Difference in rapidity of the two hardest jets. Right plot shows Higgs produced by gluon fusion and by weak boson fusion. Taken from Campbell, Ellis and WIlliams, hep-ph:1001.4495.
- Large reduction in the theoretical uncertainties of the distribution. No observed shape change.

Conclusions

- Have presented the QCD NLO calculations for the processes W^+W^+jj and W^-W^+jj using D-dimensional generalised unitarity.

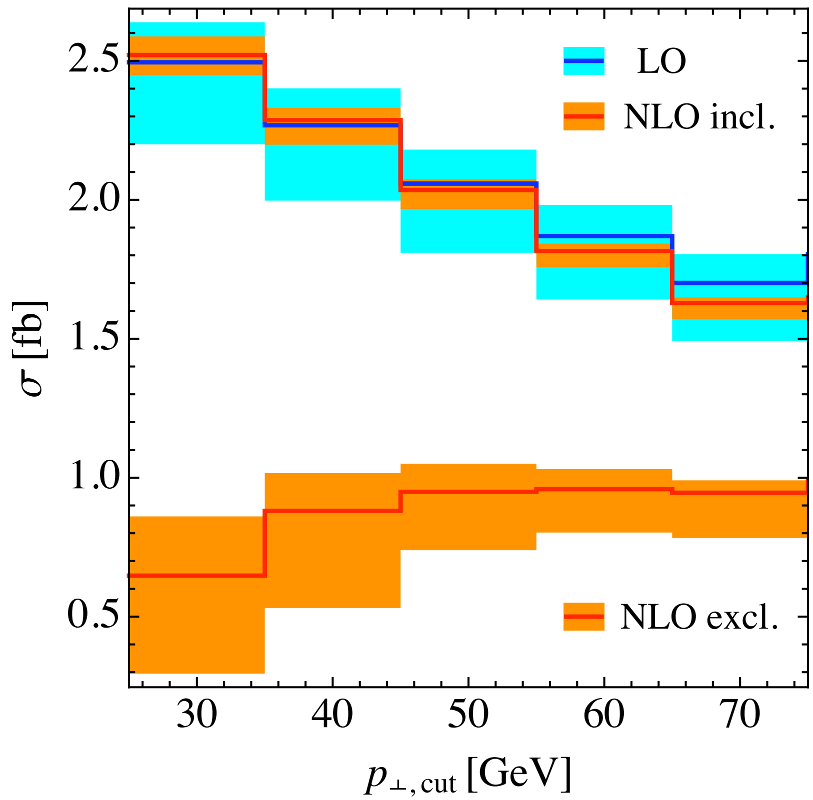
- Significant reduction in theoretical uncertainties for LHC predictions of both processes.

- W^+W^+jj has been implemented in the `POWHEG BOX` - matching NLO with a parton shower. Currently being used by an ATLAS new physics search group.

- Look forward to measurements of pairs of weak bosons and jets at the LHC!

BACKUP SLIDES

Dependence on the jet p_T cut



Here μ is varied between 100GeV and 200GeV, and the central value is 140GeV.

Shows reduction in scale dependence for a jet cut >40-50 GeV.

Whatever the exact value of exclusive 2 jet cross-section, still significantly less than the 2 jet inclusive.