

$W^+W^- + \text{jet}$ at 14 and 100 TeV

Tania Robens

based on

J. Campbell, D. Miller, TR

[Phys.Rev. D92 (2015) 1, 014033]

[see also arXiv:1601.03563, arXiv:1607.01831]

IKTP, TU Dresden

ICHEP16

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$WW + \text{jet}$: Motivation from experiment

$WW [+ \text{jet(s)}]$ at the LHC

- Measurement of **WW production cross section** [e.g. ATLAS, arXiv:1603.01702; CMS, Phys. Lett. B 721 (2013)]

⇒ **talk this morning by S. Hassani !! (8/ 13 TeV) (*)** ⇐

- $h \rightarrow WW$ measurement [e.g. ATLAS, arXiv:1607.03745; CMS, arXiv:1606.02266]
- **spin-/ parity determination** of Higgs [e.g. ATLAS, EPJC75 (2015) 231; CMS, Phys. Lett. B 759 (2016) 672]
- limits on **anomalous couplings** [e.g. ATLAS, arXiv:1607.03745; CMS, arXiv: 1411.3441] ⇒ (*) ⇐
- background for **BSM searches** (e.g. heavy scalars) [e.g. ATLAS, JHEP1601 (2016) 032; CMS, JHEP 1510 (2015) 144]
- ...

- **K-factors** $\sim 1.2 - 1.8$ [depending on analysis details, cuts, etc...]

in more detail...

Process we are interested in

$$p p \rightarrow W^+ W^- \text{jet} \rightarrow (\ell \bar{\nu}_\ell) (\bar{\ell}' \nu_{\ell'}) \text{jet}$$

at NLO, offshell W's, spin correlations

- **previous results:** Campbell, Ellis, Zanderighi [CEZ] (2007); Dittmaier, Kallweit, Uwer [DKU] (2008/ 2010), Sanguinetti/ Karg [BGKKS] (2008)
- **together with shower merging/ matching:** Cascioli ea (2014) in Sherpa/ OpenLoops framework
- also **"ad hoc" available from automatized tools** (personally tested: MG5/aMC@NLO, others probably similar...)

⇒ our approach: use **unitarity-based techniques**, derive **completely analytic expressions**

- tool/ user-interface: ⇒ **implementation in MCFM**

Unitary methods: basic idea

$$\mathcal{A}(\{p_i\}) = \sum_j d_j I_4^j + \sum_j c_j I_3^j + \sum_j b_j I_2^j + R.$$

- ⇒ know that all one-loop calculations can be reduced to **integral basis, + rational terms** [Passarino, Veltman, '78]
- ⇒ idea: **project out coefficients in front of basis integrals by putting momenta in the loop on mass shell**
(Bern, Dixon, Dunbar, Kosower ('94); Britto, Cachazo, Feng ('04))
- putting 2/3/4 particles on their mass shell projects out coefficients of a **bubble/ triangle/ box** contribution

Unitarity methods: purely analytic approaches

- as you start with a $d(4)$ -dimensional loop integral, **cutting 4 legs is easier than cutting 2**
- **boxes** \Rightarrow straightforward, using **quadruple cuts with complex momenta (BCF)**
- **triangles** \Rightarrow relatively straightforward, using **Fordes method**
- **bubbles*** \Rightarrow can get quite complicated, use **spinor integration (BBCF)**
- **rational parts** \Rightarrow long but OK, use **effective mass term (Badger)**

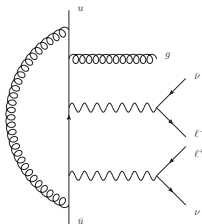
[* available in process-independent librarized format]

WWj @ NLO in more detail

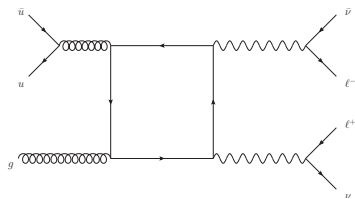
We consider

$$q \bar{q} \rightarrow W^+ W^- g \quad [+ \text{permutations}]$$

diagram classes



(a)



(b)

[+ diagrams for $q \bar{q} \rightarrow (Z/\gamma) g \rightarrow \dots$]

Coefficients: three-massive box

$$d_4(s_{56}, s_{34}, 0, s_{17}; s_{127}, s_{234}) = \frac{1}{s_{34} - m_W^2} \frac{1}{s_{56} - m_W^2} \frac{\langle 12 \rangle^2 [2|P|2]}{\langle 27 \rangle \langle 17 \rangle} \times \\ \left([42] - \frac{\langle 2|P|4 \rangle}{D_1} \right) \left(\langle 3|2 + 4|6 \rangle - \frac{\langle 23 \rangle \langle 2|P|6 \rangle}{D_1} \right) \left(\frac{[71] \langle 15 \rangle}{\langle 2|P|7 \rangle} + \frac{\langle 25 \rangle}{D_1} \right)$$

$$P = s_{17} p_{34} + s_{234} p_{17}, \quad D_2 = [2|(3+4)(1+7)|2], \quad D_1 = \langle 2|(3+4)(1+7)|2 \rangle$$

- in principle: also contributions with **second denominator**
 $D_2 = [2|(3+4)(1+7)|2]$ (here: =0)
- $D_1 D_2 \sim$ Gram determinant

Implementation: in practise

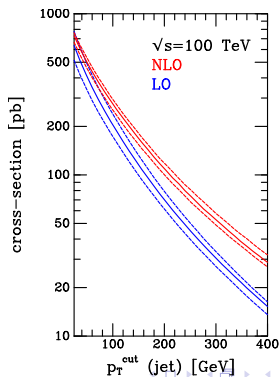
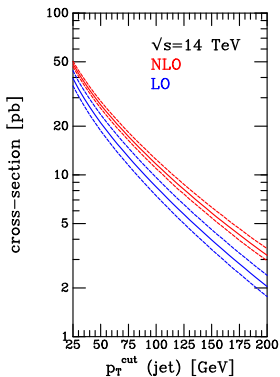
- ⇒ **fully implemented in MCFM framework**, i.e. in combination with Born, real radiation, ...
- ⇒ **MCFM output** (distributions/ cuts implementation/ interfaces/ etc...)
- in practise: **handling of expressions** ⇒ **S@M** [Maitre, Mastrolia, 2007]
[comment: also implemented in **multi-core version** [Campbell, Ellis, Giele, 2015], **now standard**]

**many cross checks: overall agreement:
amplitude/ coefficient level: 10^{-6} or better
cross section level: always within integration errors**



Phenomenology: total cross sections, as function of $p_{T,jet}^{cut}$

\sqrt{s}	σ_{LO} [pb]	σ_{NLO} [pb]
13 TeV	34.9 (-11.0%, +11.4%)	42.9 (-3.7%, +3.7%)
14 TeV	39.5 (-11.0%, +11.7%)	48.6 (-4.0%, +3.8%)
100 TeV	648 (-19.3%, +22.3%)	740 (-9.3%, +4.5%)



More phenomenology: specific studies as background

- e.g. **spin/ parity determination of SM Higgs** (ATLAS, EPJC75 (2015) 231) \Rightarrow @ 14 TeV
- e.g. **searches for additional scalars at high masses** (CMS, JHEP1510 (2015) 144) \Rightarrow @ 100 TeV

with cuts roughly following above studies...

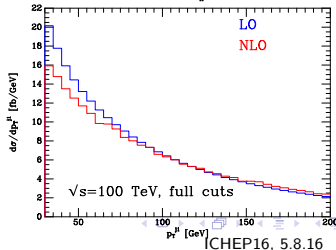
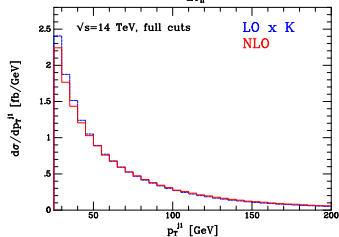
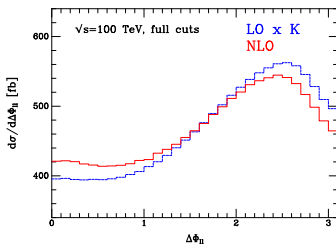
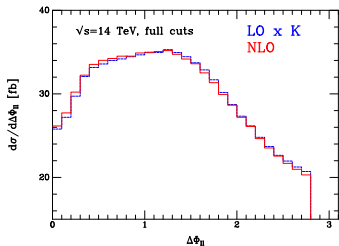
Results

order	cm energy	no cuts	K	cuts	K
LO	14 TeV	462.0(2)fb		67.12(4)fb	
NLO	14 TeV	568.4(2)fb	1.23	83.91(5)	1.25
LO	100 TeV	6815(1)fb		1237(1)fb	
NLO	100 TeV	7939(5)	1.16	1471(1)fb	1.19

Results after all cuts

14 TeV : $\sigma_{\text{LO}} = 67.128(30)\text{fb}$; $\sigma_{\text{NLO}} = 83.923(47)\text{fb}$

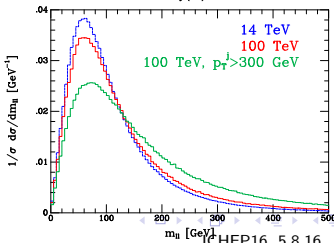
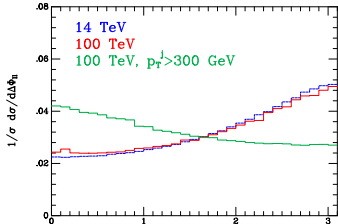
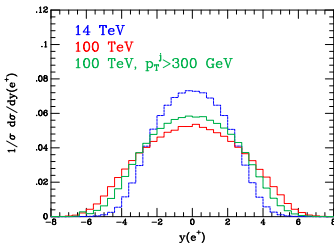
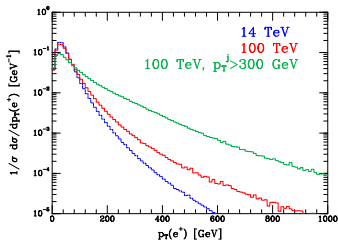
100 TeV : $\sigma_{\text{LO}} = 1237.2(4)\text{fb}$; $\sigma_{\text{NLO}} = 1472.0(7)\text{fb}$



Normalized differential distributions @ NLO

[at 14/ 100 TeV; only basic p_T^{jet} cut]

$\sigma_{\text{LO}} \sim 40 / 650 / 30$ pb, K-factors $\sim 1.23 / 1.14 / 1.77$



More on 100 TeV: giant K factors

- ⇒ **giant K factors: well-known phenomenon**, especially in connotation with "heavy" object
[widely discussed in literature]
- for vector bosons ⇒ **electroweak Sudakov factors**
 - what happens ? **NLO/LO larger than assumed/ "OK"** w perturbation theory
 - phenomenon **especially interesting when larger p_{\perp} cuts are applied**
 - physical interpretation: understanding: not α_s , but

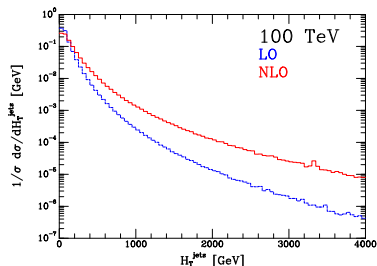
$$\alpha_s \times \log^2 [m_W/p_{\text{cut}}]$$

is the **decisive variable**

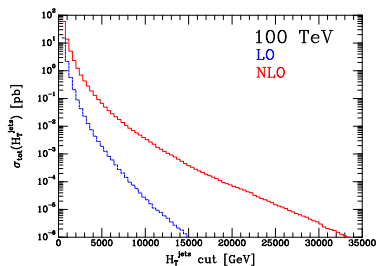
- **new initial states** come into the game

[also changes **scale dependence** (new processes enter at LO)]

Giant K factors: Example @ 100 TeV



differential, rescaled



integrated, not rescaled

in dependence of $H_{\perp}^{\text{jets}} = \sum_{\text{jets}} p_{\perp}^{\text{jet}}$

!! large cut \rightarrow large K-factor !!

Summary and outlook

$$q\bar{q} \rightarrow W^+ W^- g$$

available and implemented in MCFM, running, rendering stable results

- virtual contributions: calculated using **unitarity methods** \Rightarrow **available in analytic format**

\Rightarrow **extensively tested** on coefficient, amplitude, and cross section level \checkmark

\Rightarrow **for 100 TeV** \Leftarrow

\Rightarrow depending on background suppression, **"good" BSM selection criteria can turn bad**

\Rightarrow for certain distributions [shown here: $\sigma_{\text{tot}, p_{\perp, \text{jet}} > p_{\perp, \text{cut}}}$, H_T^{jets}] **giant K-factors (re)appear**

\Rightarrow **Thanks for listening** \Leftarrow

Appendix

Previous NLO calculations in the SM using analytic expressions from unitarity methods in MCFM

... on the amplitude level ...

- $ee \rightarrow 4$ **quarks**: Bern, Dixon, Kosower, Weinzierl (1996); Bern, Dixon, Kosower (1997)
- **Higgs and four partons** (in various configurations): Dixon, Sofianatos (2009); Badger, Glover, Mastrolia, Williams (2009); Badger, Campbell, Ellis, Williams (2009)
- $t\bar{t}$ **production**: Badger, Sattler, Yundin (2011)

... generalized unitarity implemented ...

- **Higgs + 2 jets** Campbell, Ellis, Williams (2010)
- **W + 2 b-jets** Badger, Campbell, Ellis (2011)
- $gg \rightarrow WW$ Campbell, Ellis, Williams (2011, 2014)
- $\gamma\gamma\gamma$ Campbell, Williams (2014)
- $\gamma\gamma\gamma\gamma$ Dennen, Williams (2014)

Unitarity methods: purely analytic approaches

- as you start with a $d(4)$ -dimensional loop integral, **cutting 4 legs is easier than cutting 2**
- **boxes** \Rightarrow straightforward, using **quadruple cuts with complex momenta (BCF)**
- **triangles** \Rightarrow relatively straightforward, using **Fordes method**
- **bubbles** \Rightarrow can get quite complicated, use **spinor integration (BBCF)**
- **rational parts** \Rightarrow long but OK, use **effective mass term (Badger)**

	(a)	(b)
boxes	13	1
triangles	8	4
bubbles	18	2
rational	13	5

Table: **Number of independent** (via singularity structure and/ or symmetries) **coefficients** [neglecting contributions from Z/ γ current]

- involving **1,2,3-mass boxes and triangles**,
- **bubbles: 16 different underlying structures**, involving (0/1/2) quadratic poles, e.g. [terms before spinor integration]

$$\frac{[la]^2 [lb] [lc]}{[ld][le] \langle lP|l \rangle^4}, \frac{[la] [lb] [lc]}{\langle lP|l \rangle^4 \langle lQ|l \rangle}, \frac{[la] [lb] [lc] [ld]}{\langle lP|l \rangle^4 \langle lQ|l \rangle \langle lQ_2|l \rangle}, \dots$$

Coefficients: easiest bubble and triangle

$$I_2^{\text{LC}}(s_{156}) \sim$$

$$\frac{\langle 65 \rangle [43]}{\langle 27 \rangle} \times \left\{ \frac{\langle 73 \rangle^2 \langle 7|P|6 \rangle [76]}{\langle 7|P|1 \rangle \langle 7|P|7 \rangle} \left[\frac{1}{\langle 7|P|7 \rangle} \left(\frac{[7|P|3 \rangle}{\langle 37 \rangle} + \frac{[76] s_{156}}{2 \langle 7|P|6 \rangle} \right) + \frac{[1|P|3 \rangle}{\langle 37 \rangle [1|P|7 \rangle} \right. \right. \\ \left. \left. - \frac{\langle 15 \rangle [56] [1|P|3 \rangle^2}{s_{156} \langle 1|P|1 \rangle [1|P|7 \rangle} \left[\frac{\langle 15 \rangle [56]}{2 \langle 1|P|1 \rangle} + \frac{\langle 7|P|6 \rangle}{[1|P|7 \rangle} \right] \right\}, \quad P = p_{156}$$

$$I_3^{\text{LC}}(s_{34}, s_{27}, s_{156}) \sim \frac{1}{2} \sum_{\gamma=\gamma_{1,2}} \frac{s_{27} [4K_2^b] [72] [65] \langle K_1^b 2 \rangle \langle K_1^b 3 \rangle \langle 15 \rangle^2}{(\gamma - s_{27}) [7K_2^b] \langle K_1^b 1 \rangle \langle K_1^b 7 \rangle \langle 27 \rangle}$$

where

$$K_1^b = \frac{\gamma [p_{27} + s_{27} p_{34}]}{\gamma^2 - s_{27} s_{34}}, \quad K_2^b = -\frac{\gamma [p_{34} + s_{34} p_{27}]}{\gamma^2 - s_{27} s_{34}}, \\ \gamma_{1,2} = p_{27} \cdot p_{34} \pm \sqrt{(p_{27} \cdot p_{34})^2 - s_{27} s_{34}}$$

Cross checks

- on the **amplitude as well as coefficient level**, i.e. for several ($\sim 20 - 30$) single phase space points against code using D-dimensional unitarity (Ellis, Giele, Kunszt, Melnikov, 2009)
- for a **single phase space point as well as total cross section** against comparison in Les Houches proceedings, arXiv:0803.0494 (comparison CEZ, DKU, BGKKS)
- for the latter, also **independent MG5/aMC@NLO run**

overall agreement:
amplitude/ coefficient level: 10^{-6} or better
cross section level: always within integration errors



Phenomenology

- **total cross section** as a function of $p_{T,\text{jet}}^{\text{cut}}$ for pp collisions @ **13/ 14/ 100 TeV**
- **differential distributions**, including more specific cuts
- ... for **spin- parity determination of Higgs @ 14 TeV**
- ... for **searches of extra heavy scalars @ 100 TeV**

jet definitions: anti- k_T , $p_T^{\text{jet}} > 25 \text{ GeV}$, $|\eta^{\text{jet}}| < 4.5$, $R = 0.5$

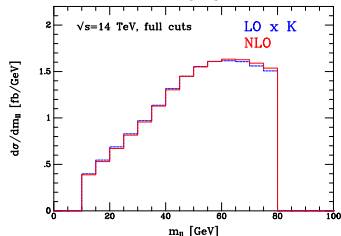
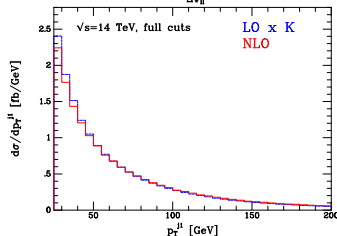
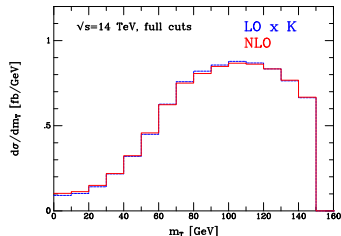
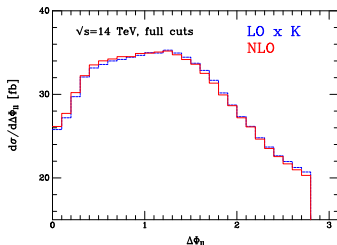
scales: $\mu_R = \mu_F = \frac{1}{2} \sum_i p_T^i$

variable	14 TeVanalysis	100 TeVanalysis
$p_{\perp,j}$	$> 25 \text{ GeV}$	30 GeV
$ \eta_j $	< 4.5	4.5
η_ℓ	≤ 2.5	2.5
p_{\perp,ℓ_1}	$> 22 \text{ GeV}$	50 GeV
p_{\perp,ℓ_2}	$> 15 \text{ GeV}$	10 GeV
$m_{\ell\ell}$	$\in [10; 80] \text{ GeV}$	–
p_{\perp}^{miss}	$> 20 \text{ GeV}$	20 GeV
$\Delta\Phi_{\ell\ell}$	< 2.8	
m_T	$\leq 150 \text{ GeV}$	$\geq 80 \text{ GeV}$
$\max[m_T^{\ell_1}, m_T^{\ell_2}]$	$> 50 \text{ GeV}$	–

$$[m_T^2 = 2 p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos \Delta\Phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}}))]$$

Results for 14 TeV after all cuts

$$\sigma_{\text{LO}} = 67.128(30)\text{fb}; \quad \sigma_{\text{NLO}} = 83.923(47)\text{fb}$$



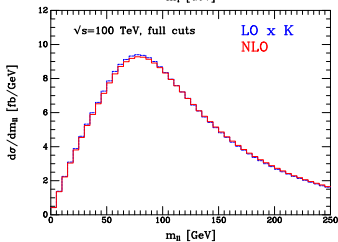
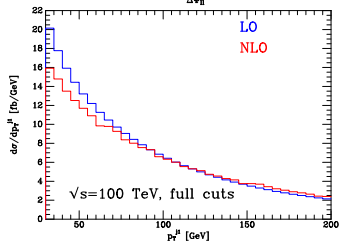
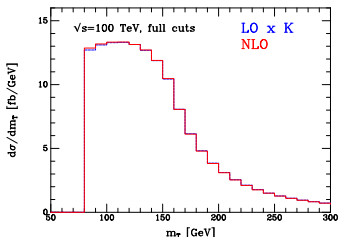
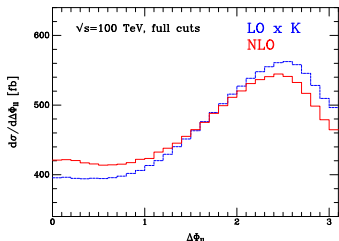
[plot: $\sigma_{\text{LO}} \times K$]

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WW + jet @ NLO

Results for 100 TeV after all cuts

$$\sigma_{\text{LO}} = 1237.2(4)\text{fb}; \quad \sigma_{\text{NLO}} = 1472.0(7)\text{fb}$$



[plot: $\sigma_{\text{LO}} \times K$]

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WW + jet @ NLO

Questions one can ask at a 100 TeV hh collider

[loose compilation]

⇒ **Question 1** (for the BSM physicist):

do I have to rethink my cut strategies ??

- tentative answer: in the end, **MVA might do it all for you**, but maybe worth thinking about it anyways

⇒ **Question 2:** within the SM, is the **behaviour the same at higher energies ??**

[more specific, what about **role of "heavy" objects** for increased c.o.m energies ⇒ probably will be discussed in follow up talks...]

- buzzword for 2: **giant K-factors**

⇒ **Question 3:** ... ??

Setup for 100 TeV studies

jet definitions: anti- k_T , $p_T^{\text{jet}} > 25 \text{ GeV}$, $|\eta^{\text{jet}}| < 4.5$, $R = 0.5$
scales: $\mu_R = \mu_F = \frac{1}{2} \sum_i p_T^i$

\sqrt{s}	$p_{\perp,\text{cut}}^{\text{jet}}$	$\sigma_{LO} [\text{pb}]$	$\sigma_{NLO} [\text{pb}]$
14 TeV	25 GeV	$39.5^{+11.7\%}_{-11.0\%}$	$48.6^{+3.8\%}_{-4.0\%}$
100 TeV	25 GeV	$648^{+22.3\%}_{-19.3\%}$	$740^{+4.5\%}_{-9.3\%}$
100 TeV	300 GeV	$30.3^{+11.22\%}_{-10.56\%}$	$53.7^{+8.0\%}_{-7.6\%}$

⇒ note **larger K factor** when $p_{\perp,\text{cut}}$ is increased ⇐

One slide of self-commercial

- calculation of **bubble-coefficients: process-independent**
- ⇒ **mathematica-based library**, with (all) librarised poles for ~ 20 different structures
- ⇒ can **apply these completely straightforward to any other calculation** where the same structures appear in bubble (and can also obviously extend this)
- current interface: **me**
- future plan: **make public** in librarized format

all tested (✓)

but obviously not every possible structure available at the moment

Basis integrals, type (a)

$D^{(1)}$	$I_4(0, 0, s_{56}, s_{234}; s_{17}, s_{156})$
$D^{(2)}$	$I_4(s_{34}, s_{56}, 0, s_{27}; s_{127}, s_{156})$
$D^{(3)}$	$I_4(0, 0, s_{34}, s_{156}; s_{27}, s_{234})$
$D^{(4)}$	$I_4(s_{56}, s_{34}, 0, s_{17}; s_{127}, s_{234})$
$D^{(5)}$	$I_4(0, 0, 0, s_{127}; s_{17}, s_{27})$
$C^{(1)}$	$I_3(0, s_{234}, s_{156})$
$C^{(2)}$	$I_3(s_{56}, s_{17}, s_{234})$
$C^{(3)}$	$I_3(s_{34}, s_{27}, s_{156})$
$C^{(4)}$	$I_3(0, s_{27}, s_{127})$
$C^{(5)}$	$I_3(0, s_{17}, s_{127})$
$C^{(6)}$	$I_3(0, 0, s_{17})$
$C^{(7)}$	$I_3(0, s_{56}, s_{156})$
$C^{(8)}$	$I_3(s_{56}, s_{34}, s_{127})$
$C^{(9)}$	$I_3(0, 0, s_{27})$
$C^{(10)}$	$I_3(0, s_{34}, s_{234})$
$B^{(1)}$	$I_2(s_{156})$
$B^{(2)}$	$I_2(s_{234})$
$B^{(3)}$	$I_2(s_{56})$
$B^{(4)}$	$I_2(s_{17})$
$B^{(5)}$	$I_2(s_{34})$
$B^{(6)}$	$I_2(s_{127})$

$D^{(6)}$	$I_4(s_{56}, s_{34}, 0, s_{17}; s_{127}, s_{234})$
$D^{(7)}$	$I_4(0, 0, 0, s_{127}; s_{27}, s_{12})$
$D^{(8)}$	$I_4(0, 0, 0, s_{127}; s_{17}, s_{12})$
$D^{(9)}$	$I_4(s_{34}, 0, 0, s_{567}; s_{234}, s_{12})$
$D^{(10)}$	$I_4(s_{34}, s_{12}, s_{56}, 0; s_{567}, s_{347})$
$D^{(11)}$	$I_4(0, 0, s_{56}, s_{347}; s_{12}, s_{156})$
$D^{(12)}$	$I_4(s_{34}, s_{12}, 0, s_{56}; s_{567}, s_{127})$
$D^{(13)}$	$I_4(0, s_{12}, s_{56}, s_{34}; s_{127}, s_{347})$
$C^{(11)}$	$I_3(0, 0, s_{27})$
$C^{(12)}$	$I_3(0, s_{34}, s_{234})$
$C^{(13)}$	$I_3(0, s_{34}, s_{347})$
$C^{(14)}$	$I_3(0, s_{347}, s_{156})$
$C^{(15)}$	$I_3(0, s_{127}, s_{12})$
$C^{(16)}$	$I_3(0, 0, s_{12})$
$C^{(17)}$	$I_3(s_{34}, s_{567}, s_{12})$
$C^{(18)}$	$I_3(s_{56}, s_{347}, s_{12})$
$B^{(7)}$	$I_2(s_{567})$
$B^{(8)}$	$I_2(s_{347})$
$B^{(9)}$	$I_2(s_{12})$

Table: scalar integrals of type (a) *left* leading colour and *right* additional subleading color amplitude.

Basis integrals, type (b)

$D^{(10)}$	$I_4(s_{34}, s_{12}, s_{56}, 0; s_{567}, s_{347})$
$D^{(12)}$	$I_4(s_{34}, s_{12}, 0, s_{56}; s_{567}, s_{127})$
$D^{(13)}$	$I_4(0, s_{12}, s_{56}, s_{34}; s_{127}, s_{347})$
$C^{(8)}$	$I_3(0, s_{56}, s_{567})$
$C^{(10)}$	$I_3(s_{56}, s_{34}, s_{127})$
$C^{(13)}$	$I_3(0, s_{34}, s_{347})$
$C^{(15)}$	$I_3(0, s_{127}, s_{12})$
$C^{(17)}$	$I_3(s_{34}, s_{567}, s_{12})$
$C^{(18)}$	$I_3(s_{56}, s_{347}, s_{12})$
$B^{(3)}$	$I_2(s_{56})$
$B^{(5)}$	$I_2(s_{34})$
$B^{(6)}$	$I_2(s_{127})$
$B^{(7)}$	$I_2(s_{567})$
$B^{(8)}$	$I_2(s_{347})$
$B^{(9)}$	$I_2(s_{12})$

Table: Definitions of the scalar integrals that appear in the calculation of the diagrams of type (b), leading colour only.

Appearance of quadratic poles/ square roots

- have a cut leading to a propagator $\sim \frac{1}{s_{\ell_1 p}}$, where $p^2 \neq 0$ (e.g. $p = p_1 + p_2$)
- for spinor integration $\ell_1 \rightarrow \frac{P^2}{[\ell|P|\ell]} \ell$, where P is momentum over the cut
- i.e., use

$$s_{\ell_1, p} = \langle \ell_1 | \not{p} | \ell_1 \rangle + p^2 \rightarrow \frac{P^2 \langle \ell | \not{p} | \ell \rangle}{\langle \ell | \not{P} | \ell \rangle} + p^2 = \frac{\langle \ell | \not{Q} | \ell \rangle}{\langle \ell | \not{P} | \ell \rangle},$$

- contributions often appear together with factors $\sim \frac{1}{\langle \ell | \not{P} | \ell \rangle}$
- \Rightarrow contains poles $\sim \frac{1}{\langle \ell | \not{PQ} | \ell \rangle}$
- leads to two possible solutions for $|\ell\rangle$ where $\langle \ell | \not{PQ} | \ell \rangle = 0$ (pole)

Electroweak parameters

m_W	80.385 GeV	Γ_W	2.085 GeV
m_Z	91.1876 GeV	Γ_Z	2.4952 GeV
e^2	0.095032	g_W^2	0.42635
$\sin^2 \theta_W$	0.22290	G_F	0.116638×10^{-4}

Effect of neglecting diagrams containing Higgs/ diagrams with top loops

- in MG5/aMC@NLO: top and Higgs included
- check: run with $m_t m_H \times 10$ (100)
- results

calculation	parameters	σ^{NLO} [pb]
MCFM	default	14.571 (18)
MG5	default	14.547 (19)
MG5	$m_h \times 10, m_t \times 10$	14.615 (21)
MG5	$m_h \times 100, m_t \times 100$	14.563 (19)
DKU	default	14.678 (10)

Other (related) (reduction) methods [non-exhaustive listing]

- **purely analytic: generalized unitarity** [Britto, (Buchbinder), Cachazo, Feng (2005, 2006); Britto, Feng, Mastrolia (2006), Forde (2007), Badger (2009), Mastrolia (2009), ...]
- other approaches: **recursion/ reduction methods** [Berends, Giele (1987); del Aguila, Pitta (2004); Ossola, Papadopoulos, Pittau (2006)]
- **numerical implementations** in many (publicly available) codes: (in order of appearance) **CutTools** (OPP, 2007), **Samurai** (Mastrolia ea, 2010), **Gosam** (Cullen ea, 2011), **MadLoop/aMC@NLO** (Hirschi ea, 2011, Frederix ea, 2011), **Helac-NLO** (van Hameren ea, 2010; Bevilacqua ea, 2013)
- **other numerical implementations** (in order of appearance): **Blackhat** (Berger ea, 2008), **Rocket** (Giele, Zanderighi, 2008), **NGluon** (Badger ea, 2011), **OpenLoops** (Cascioli ea, 2011), **Ninja** (Peraro, 2014)

Disentangle this for our process

- (a) initial states also existing **at LO** (in our calculation):
 $q \bar{q}$ (osf), $g q$, $g \bar{q}$
 - (b) new initial states **at NLO**, type I: gg
 - (c) new initial states **at NLO**, type II: qq' , $q\bar{q}'$, $\bar{q}q'$,
(': different flavour)
 - in practise: (b), (c) often suppressed using **2nd jet veto** [well-known procedure...]
 - **type II also contribute on cases of same sign W's**
(obviously in different flavour combinations)
- ⇒ test channel contributions wrt different cut setups ⇐**

[all above: excludes WBF channels]