

Weak boson pair production at the LHC

Nikolas Kauer

Centre for Particle Physics
Royal Holloway, University of London

in collaboration with

T. Binoth, M. Ciccolini, T. Gleisberg, S. Karg, M. Krämer, P. Mertsch, G. Sanguinetti;
J. M. Campbell, E. Castaneda-Miranda, Y. Fang, B. Mellado, S. L. Wu

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Outline

- Introduction
- Weak bosons: importance for LHC physics
- Weak boson pair (+ jets) production
- Gluon-induced WW, ZZ background to Higgs searches
- NLO QCD calculations for $WW, ZZ + \text{jet}$
- Normalising weak boson pair production at the LHC
- Scale choice dependence of observables
- Standardisation of NLO computations
- Summary

The Large Hadron Collider (re)starts ... soon

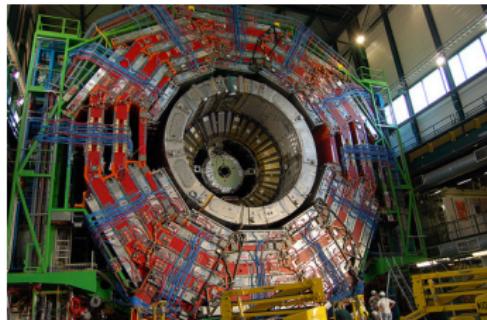
Protons colliding at 14 Tera-eV $\approx 15000 M_p c^2 \sim 10^{-6}$ J total energy

14 TeV collision: 2 ping pong balls (3 g) colliding at $v = 2.7$ cm/s, $M_p \sim 10^{-24} M_{\text{ping pong ball}}$

7 × higher collision energy than Tevatron, 50 × higher std. reaction rate (luminosity) than Tevatron



100 billion protons per bunch, 2800 bunches in each direction on **27 km length**, total beam energy of 300 Mega-Joules = 120 kg TNT, melts ≈ 1 ton of copper, collisions at 40 MHz \rightarrow 1 Terabyte raw detector data per second, Higgs particle would be produced in 5 out of 1 billion collisions (J. Lykken: *Is particle physics ready for the LHC?*)



source: CERN/ATLAS/CMS archive

Discoveries at the LHC

Discovery convention



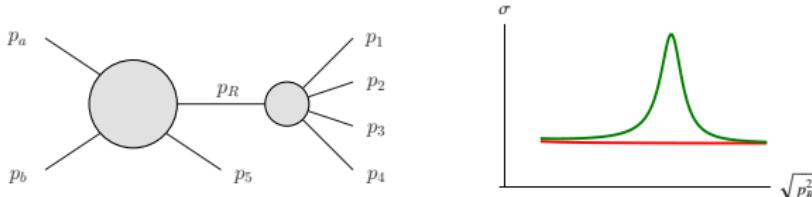
S = nr. of signal events, B = nr. of background events,

Observation significance: $\sigma = S/\sqrt{B + S}$

Discovery if $\sigma \geq 5 \rightarrow P(\text{background fluctuation}) \leq 2.85 \times 10^{-7}$

Discoveries require the accurate determination of
rates and uncertainties for signals and backgrounds

The experimentally ideal case: a new, reconstructible mass peak



p_1, p_2, p_3, p_4 measurable $\rightarrow p_R = p_1 + p_2 + p_3 + p_4$

\rightarrow invariant mass distribution from experimental data (\rightarrow resonance mass and width)

\rightarrow background via sideband interpolation (\rightarrow signal)

but: neutrinos and dark matter candidates not detectable at the LHC

Weak bosons in the Standard Model

Quarks	u	c	t	γ
	up	charm	top	photon
d	s	b	g	gluon
Leptons	ν_e	ν_μ	ν_τ	W boson
	e	μ	τ	Z boson
electron	muon	tau		

Poincare-invariant, renormalisable quantum field theory (QFT)
with local gauge invariance $SU(3) \times SU(2)_L \times U(1)$
 \rightarrow vector bosons g, W^\pm, Z, γ

Weak bosons and electroweak symmetry breaking

gauge boson and fermion **mass terms not gauge invariant**

Gauge boson in theory with local $U(1)$ gauge symmetry:

$$\mathcal{L} = -\frac{1}{2}F_{\mu\nu}F^{\mu\nu} \text{ with } F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Mass term $m^2 A_\mu A^\mu$ not gauge invariant, but $m_W, m_Z > 0$.

Fermion mass term $m\bar{\psi}\psi = m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L$ not invariant under $SU(2)_L$, but $m_f > 0$.

Spontaneous symmetry breaking in the Standard Model via $SU(2)$ doublet Φ and $V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$:

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \quad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$SU(2)_L \times U(1)_Y \xrightarrow{\text{SSB}} U(1)_{em}$, i.e. 4 → 1 symmetry generators

massive: $Z_\mu \propto (gW_\mu^{(3)} - g'B_\mu)$, $W_\mu^\mp \propto (W_\mu^{(1)} \pm W_\mu^{(2)})$ and Higgs H , massless: A_μ

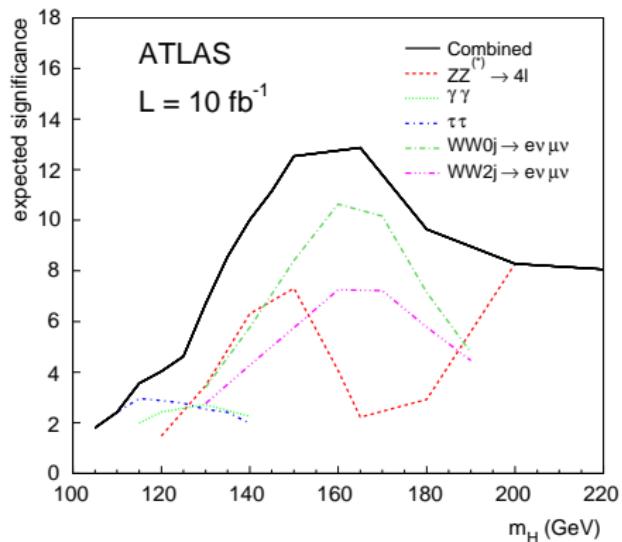
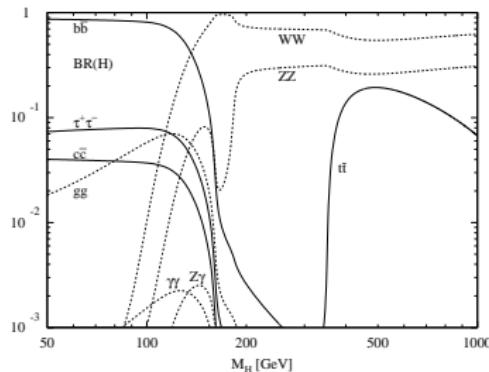
Weak bosons: importance for LHC physics

LHC search for New Physics (SUSY, ...)

- ▶ dark matter candidate → signatures with \cancel{E}_T
- ▶ cascade decays with new EW gauge bosons/gauginos → ℓ^\mp
- ▶ cascade decays of new coloured particles → jets

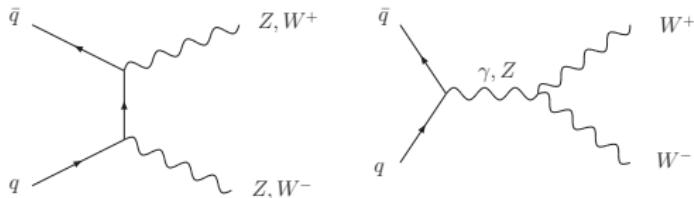
W, Z decay into ℓ^\mp and/or ν or jets → same signatures → important backgrounds

LHC search for SM & BSM Higgs



$H \rightarrow VV$ searches: dominant irreducible background is VV (+ jets)

Predictions for weak boson pair production



- e^+e^- , $pp, p\bar{p} \rightarrow ZZ, WW$ at LO (and decays)

Brown, Mikaelian (1979); Stirling, Kleiss, S. Ellis (1985); Gunion, Kunszt (1986); Muta, Najima, Wakaizumi (1986); Berends, Kleiss, Pittau (1994) [$e^+e^- \rightarrow f_1\bar{f}_2f_3\bar{f}_4$ at LO]

- $pp, p\bar{p} \rightarrow ZZ, WW, WZ$ at NLO QCD (with leptonic decays)

Ohnemus (1991); Mele, Nason, Ridolfi (1991); Ohnemus, Owens (1991); Frixione (1993); Ohnemus (1994); Dixon, Kunszt, Signer (1998, 1999); Campbell, K. Ellis (1999) [$pp, p\bar{p} \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ at NLO QCD]

- $gg \rightarrow ZZ, WW$ (with leptonic decays), (1-loop)² NNLO QCD correction
Dicus, Kao, Repko (1987); Glover, van der Bij (1989); Kao, Dicus (1991); Matsuura, v.d. Bij (1991); Zecher, Matsuura, v.d. Bij (1994); Dührssen, Jakobs, v.d. Bij, Marquard (2005); Bineth, Ciccolini, NK, Krämer (2005, 2006); Bineth, NK, Mertsch (2008)
- 2-loop-virtual–Born interference for $q\bar{q} \rightarrow WW \rightarrow$ NNLO QCD correction
Chachamis, Czakon, Eiras (2008)

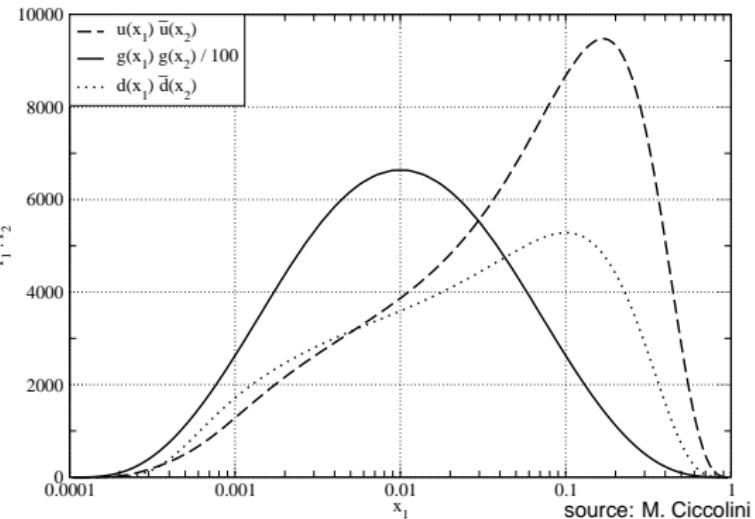
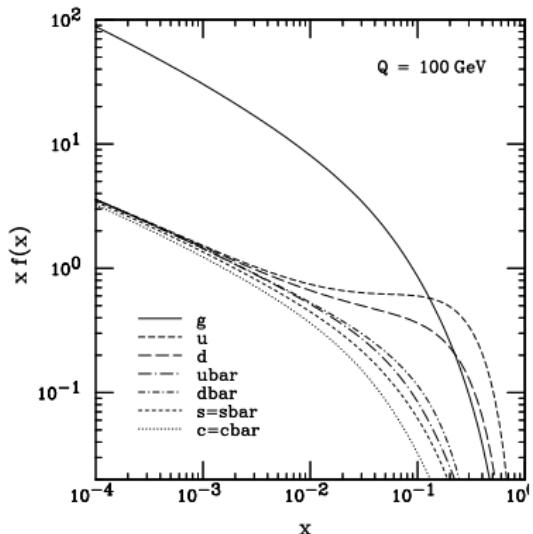
Predictions for weak boson pair + jets production

- $pp, p\bar{p} \rightarrow WW + \text{jet}$ at NLO QCD (with leptonic decays)
Dittmaier, Kallweit, Uwer (2007); Campbell, K. Ellis, Zanderighi (2007)
- Weak boson fusion contribution to $pp \rightarrow WW + 2 \text{ jets}, ZZ + 2 \text{ jets}, WZ + 2 \text{ jets}$ at NLO QCD with leptonic decays
B. Jäger, Oleari, Zeppenfeld (2006); Bozzi, B. Jäger, Oleari, Zeppenfeld (2007)

$$pp \rightarrow WW, ZZ \rightarrow 4\ell \text{ at } \mathcal{O}(\alpha_s^2)$$

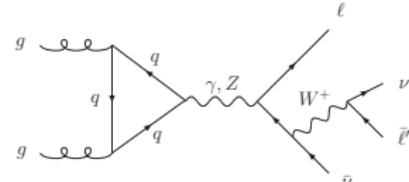
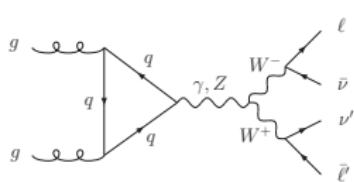
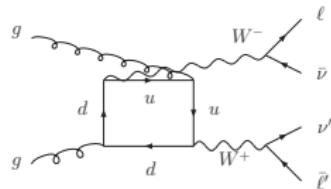
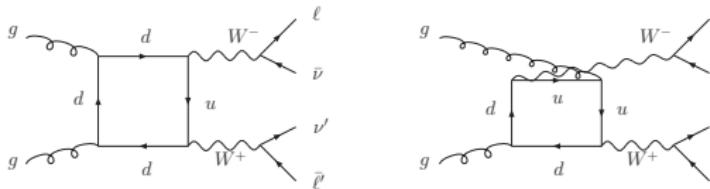
Why (partial) NNLO calculation? New subprocess $gg \rightarrow WW, ZZ \rightarrow 4\ell!$

- ▶ enhanced by large gluon-gluon flux at the LHC
- ▶ boost of VV system only in $q\bar{q}$ scattering
- ▶ more similar to $gg \rightarrow H \rightarrow VV$ signal



CTEQ6M, $x_1 \cdot x_2 = \hat{s}/s = m_{VV}^2/s \approx 10^{-4} = 0.01^2$, (orig. cut: $\cos \theta_{\ell\ell, \text{beam}} < 0.8$)

WW calculation



Binoth, Ciccolini, NK, Krämer (2005,2006)

- ▶ two independent calculations; checked against results in literature
- ▶ external leptons: massless; internal quarks: massless + massive (t, b)
- ▶ arbitrary invariant masses for W bosons (off-shell effects)
- ▶ gauge-invariant amplitude with full polarization/spin correlations
- ▶ $gg \rightarrow H \rightarrow WW$ amplitude included (signal-background interference)
- ▶ $\mu_{ren,fac} = M_W$, CTEQ6M, G_μ scheme ($\alpha(0), \alpha(M_Z)$): $\mp 10\%$
- ▶ tools: FeynArts, LoopTools [Hahn](#), FORM [Vermaseren](#)

WW signal and background cross sections

$\sigma(pp \rightarrow W^*W^* \rightarrow \ell\nu\bar{\ell}\nu') [\text{fb}], \text{ LHC}, M_W/2 \leq \mu_{\text{ren,fac}} \leq 2M_W$					
	$q\bar{q}$	gg	$\frac{\sigma_{gg,3\text{gen}}}{\sigma_{gg,2\text{gen}}}$	$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$	$\frac{\sigma_{\text{NLO+gg}}}{\sigma_{\text{NLO}}}$
	LO	NLO			
σ_{tot}	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	$60.00(1)$ $53.64(1)^{+14.0}_{-10.8}$	1.12	1.57 1.04
σ_{std}	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	$29.79(2)$ $25.89(1)^{+6.85}_{-5.29}$	1.15	1.82 1.05
σ_{bkg}	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	$1.4153(3)$ $1.3837(3)^{+0.40}_{-0.31}$	1.02	1.05 1.30 1.29

2 massless generations, 3 generations

standard LHC cuts (**std. cuts**): $p_T \ell > 20 \text{ GeV}, |\eta_\ell| < 2.5, \not{p}_T > 25 \text{ GeV}$

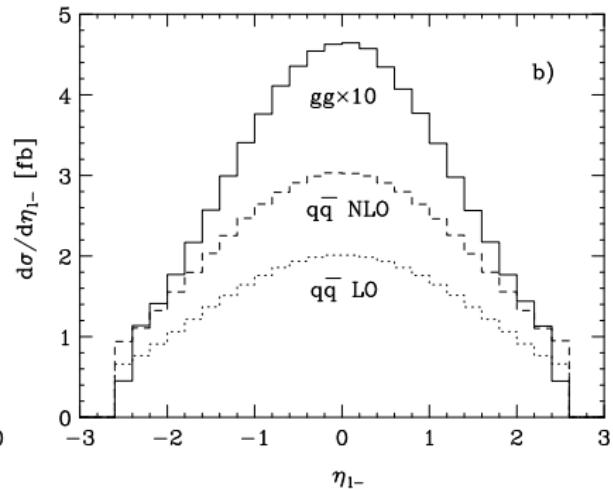
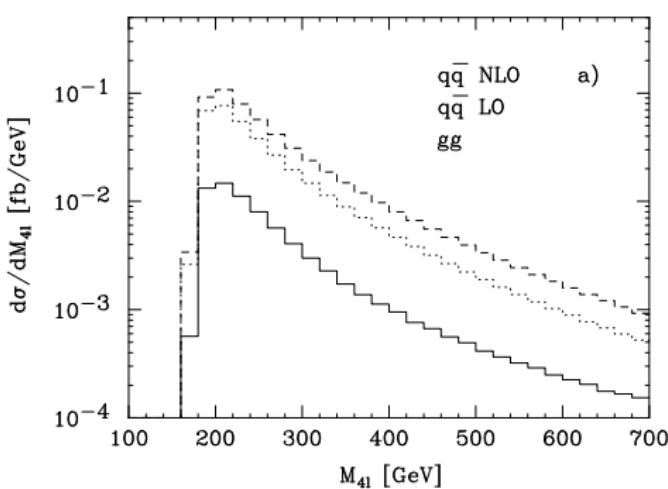
bkg. cuts = std. cuts and **Higgs search cuts**:

$\Delta\phi_{T,\ell\ell} < 45^\circ, m_{\ell\ell} < 35 \text{ GeV}, \text{jet veto: } p_T j > 20 \text{ GeV and } |\eta_j| < 3,$
 $35 \text{ GeV} < p_{T\ell,\text{max}} < 50 \text{ GeV}, 25 \text{ GeV} < p_{T\ell,\text{min}}$

selection: Davatz, Dissertori, Dittmar, Grazzini, Pauss (2004)

ZZ background to $pp \rightarrow H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$

$\sigma(pp \rightarrow Z^*(\gamma^*)Z^*(\gamma^*) \rightarrow \ell\bar{\ell}\ell'\bar{\ell}') [\text{fb}]$				
	gg	$q\bar{q}$		$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$
		LO	NLO	
σ_{std}	1.492(2)	7.343(1)	10.953(2)	1.49
				1.14

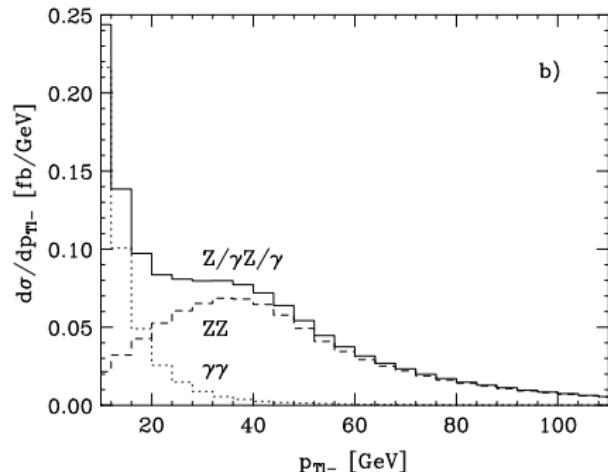
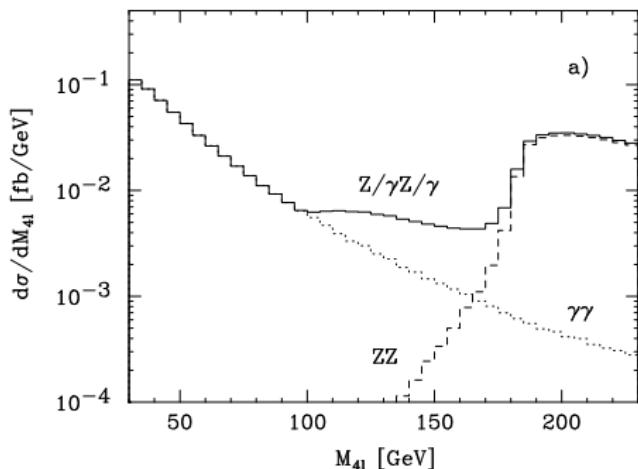


std. cuts applied: $p_{T\ell} > 20 \text{ GeV}$, $|\eta_\ell| < 2.5$, $75 \text{ GeV} < M_{\ell^+\ell^-} < 105 \text{ GeV}$

Binoth, NK, Mertsch (2008)

ZZ background to $pp \rightarrow H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

Importance of virtual photon contributions if $M_H < 2M_Z$:



$gg \rightarrow Z^*(\gamma^*)Z^*(\gamma^*) \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$, minimal cuts applied: $M_{\ell^+\ell^-} > 5$ GeV

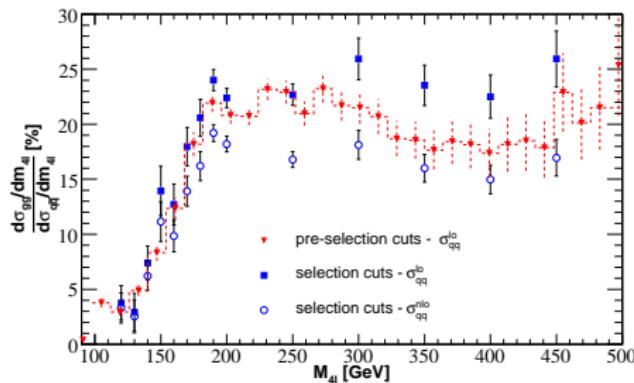
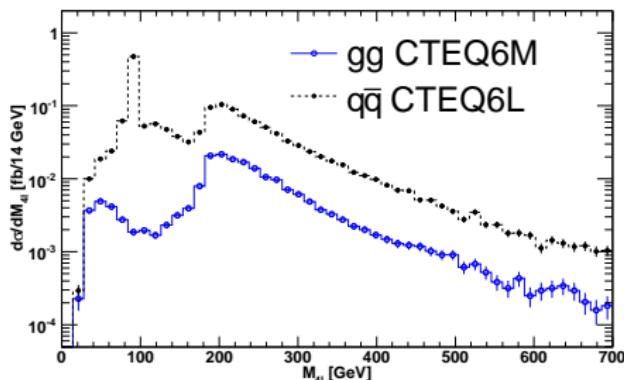
GG2VV parton-level MC integrators & event generators

<http://hepsource.sf.net/programs/>

- ▶ include full spin correlations, off-shell & interference effects
- ▶ generate unweighted events in Les Houches standard format
- ▶ user-friendly specification of selection cuts and histograms
- ▶ adaptive MC integration with parallel mode (OmniComp-Dvegas)

used by ATLAS and CMS for $H \rightarrow VV$ studies

$gg \rightarrow Z^*(\gamma^*)Z^*(\gamma^*)$ background simulation for Higgs boson search



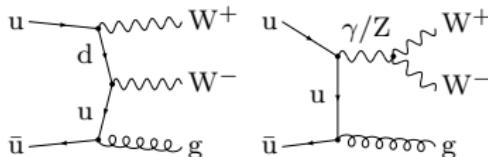
Giordano [CMS] (2008)

NLO QCD calculation for $WW + \text{jet}$

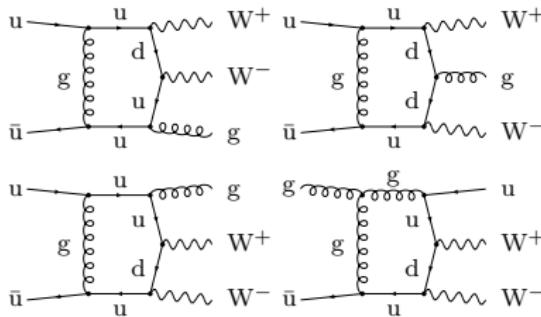
$pp \rightarrow VV + \text{jet}$ @ NLO is component of $pp \rightarrow VV$ @ NNLO

6 subprocesses: $q\bar{q} \rightarrow WWg$, $qg \rightarrow WWq$, $\bar{q}g \rightarrow WW\bar{q}$ with $q = u, d$

LO amplitude contributions



Virtual corrections contributions



Real corrections: crossings of $0 \rightarrow WWq\bar{q}gg$ and $0 \rightarrow WWq\bar{q}q'\bar{q}'$

graphs source: arXiv:0710.1577

WWj : tuned comparison of three groups

Results for a single phase-space point

Bosonic virtual corrections:

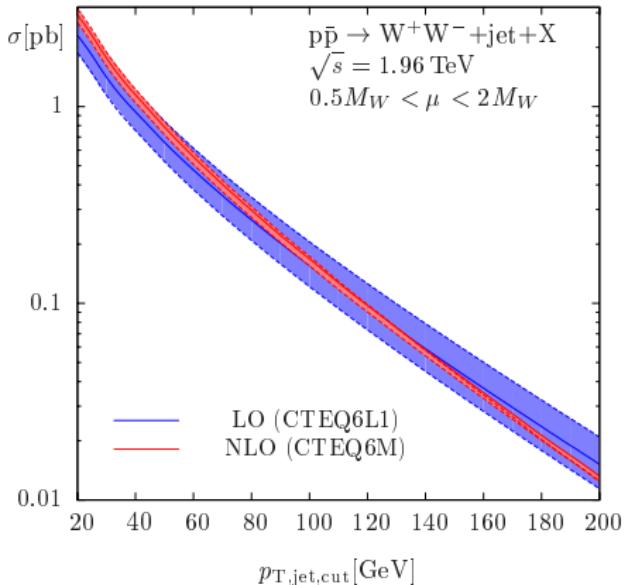
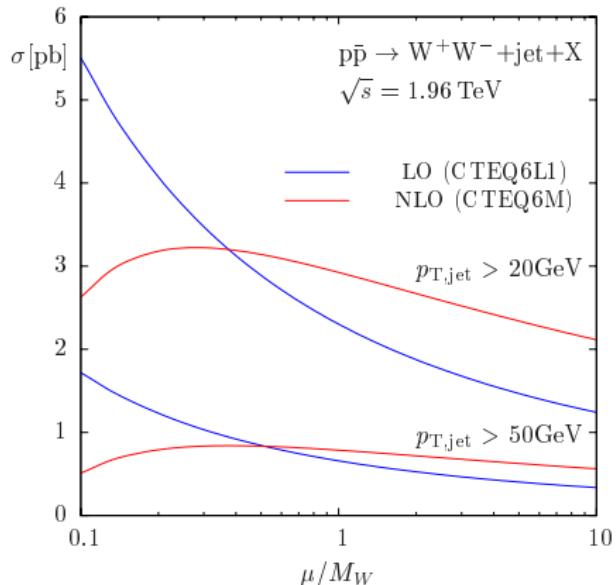
$$2\text{Re}\{\mathcal{M}_V^* \cdot \mathcal{M}_{\text{LO}}\} = e^4 g_s^2 \Gamma(1 + \varepsilon) (4\pi\mu_{\text{ren}}^2/M_W^2)^\varepsilon (c_{-2}/\varepsilon^2 + c_{-1}/\varepsilon + c_0)$$

Dittmaier, Kallweit, Uwer (DKU); Campbell, K. Ellis, Zanderighi (CEZ); Bineth, Guillet, Karg, NK, Sanguinetti (BGKKS)

	$c_{-2} [\text{GeV}^{-2}]$	$c_{-1}^{\text{bos}} [\text{GeV}^{-2}]$	$c_0^{\text{bos}} [\text{GeV}^{-2}]$
$u\bar{u} \rightarrow W^+W^-g$			
DKU	$-1.080699305508758 \cdot 10^{-4}$	$7.842861905263072 \cdot 10^{-4}$	$-3.382910915425372 \cdot 10^{-3}$
CEZ	$-1.080699305505865 \cdot 10^{-4}$	$7.842861905276719 \cdot 10^{-4}$	$-3.382910915464027 \cdot 10^{-3}$
BGKKS	$-1.080699305508814 \cdot 10^{-4}$	$7.842861905263293 \cdot 10^{-4}$	$-3.382910915616242 \cdot 10^{-3}$
$d\bar{d} \rightarrow W^+W^-g$			
DKU	$-3.987394716797222 \cdot 10^{-7}$	$2.893736116870099 \cdot 10^{-6}$	$-1.252531649334637 \cdot 10^{-5}$
CEZ	$-3.987394716665197 \cdot 10^{-7}$	$2.893736115389983 \cdot 10^{-6}$	$-1.252531614999332 \cdot 10^{-5}$
BGKKS	$-3.987394716798342 \cdot 10^{-7}$	$2.893736117550454 \cdot 10^{-6}$	$-1.252531647620369 \cdot 10^{-5}$
$ug \rightarrow W^+W^-u$			
DKU	$-1.675029833503229 \cdot 10^{-5}$	$1.236268430131559 \cdot 10^{-4}$	$-5.417120947927877 \cdot 10^{-4}$
CEZ	$-1.675029833501256 \cdot 10^{-5}$	$1.236268430124113 \cdot 10^{-4}$	$-5.417120948004078 \cdot 10^{-4}$
BGKKS	$-1.675029833503285 \cdot 10^{-5}$	$1.236268430131930 \cdot 10^{-4}$	$-5.417120948184518 \cdot 10^{-4}$
$dg \rightarrow W^+W^-d$			
DKU	$-1.667890693078443 \cdot 10^{-7}$	$1.231000679615805 \cdot 10^{-6}$	$-5.402644808236175 \cdot 10^{-6}$
CEZ	$-1.667890693268847 \cdot 10^{-7}$	$1.230999331981130 \cdot 10^{-6}$	$-5.402644353170802 \cdot 10^{-6}$
BGKKS	$-1.667890693077475 \cdot 10^{-7}$	$1.230999333576065 \cdot 10^{-6}$	$-5.402644211736123 \cdot 10^{-6}$
$g\bar{u} \rightarrow W^+W^-\bar{u}$			
DKU	$-8.125284951799448 \cdot 10^{-6}$	$7.047108864062224 \cdot 10^{-5}$	$-3.525581727244482 \cdot 10^{-4}$
CEZ	$-8.125284951286924 \cdot 10^{-6}$	$7.047108863931619 \cdot 10^{-5}$	$-3.525581728065669 \cdot 10^{-4}$
BGKKS	$-8.125284951799859 \cdot 10^{-6}$	$7.047108864102780 \cdot 10^{-5}$	$-3.525581727287365 \cdot 10^{-4}$
$g\bar{d} \rightarrow W^+W^-\bar{d} \dots$			

Les Houches 2007 proceedings

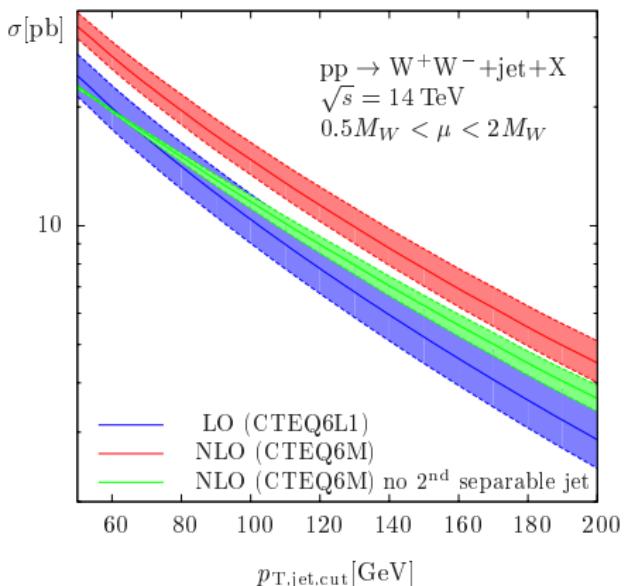
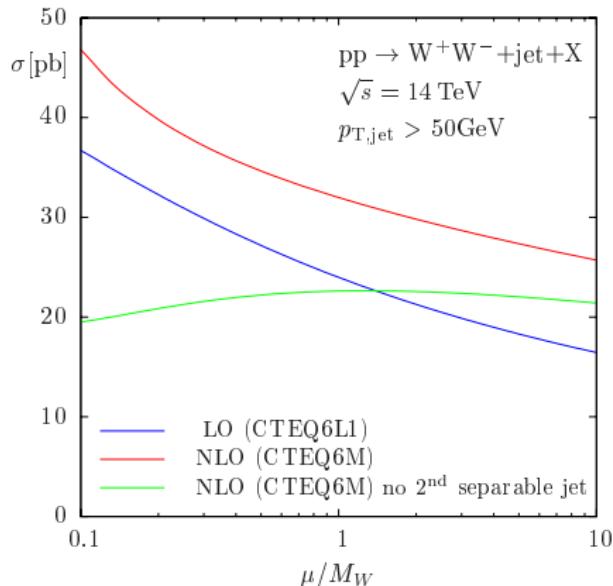
WWj : Tevatron results



LO: $q\bar{q} : 90\%$, $qg : 5\%$, $\bar{q}g : 5\%$, $\mu := \mu_R = \mu_F \in [M_W/4, 4M_W] \rightarrow 70\%$

Dittmaier, Kallweit, Uwer

WWj : LHC results



LO: $qg : 56\%$, $q\bar{q} : 28\%$, $\bar{q}g : 16\%$, $\mu := \mu_R = \mu_F \in [M_W/4, 4M_W] \rightarrow 25\%$

Dittmaier, Kallweit, Uwer

NLO QCD calculation for $Z Z + \text{jet}$

T. Binoth, T. Gleisberg, S. Karg, NK, G. Sanguinetti

Virtual correction: GOLEM tensor reduction approach

Binoth, Heinrich (2004); Binoth, Guillet, Heinrich, Pilon, Schubert (2005)

6 distinct subprocesses (u,d sep.), ~ 200 Feynman graphs, 36 helicity combinations, 't Hooft-Veltman and $\overline{\text{MS}}$ schemes

2→3 status: complete and cross checked except for collinear term

Real correction: Catani-Seymour dipole subtraction

Catani, Seymour (1996); Catani, Dittmaier, Seymour, Trocsanyi (2002)

$p_1 p_2 \rightarrow ZZ p_3 p_4$: 21 subprocesses, on avg. 6 dipoles per subprocess,
 ~ 1200 Feynman graphs in total

Amplitude and subtraction terms:

Sherpa Gleisberg, Krauss (2007) and MadGraph Stelzer et al. (1994) + Mad-Dipole Frederix, Gehrmann, Greiner (2008); 2nd cross check: Helac dipoles Czakon, Papadopoulos, Worek (2009) ✓

2→4 status: complete, 9 digit agreement for $|\mathcal{M}_R|^2$ and all dipoles ✓, not yet
cross checked: multi-channel PS

$ZZ + \text{jet}$: preliminary results

Input parameters/settings:

$$N_F = 5 \quad (M_q = 0)$$

$$M_Z = 91.188 \text{ GeV}$$

$$\alpha(M_Z) = 0.00755391226$$

PDF: CTEQ6L1 (LO), CTEQ6M (NLO) [Pumplin et al. \(2002\)](#)

$$\sin^2 \theta_W = 0.222247$$

central scale choice: $\mu_R = \mu_F = M_Z$

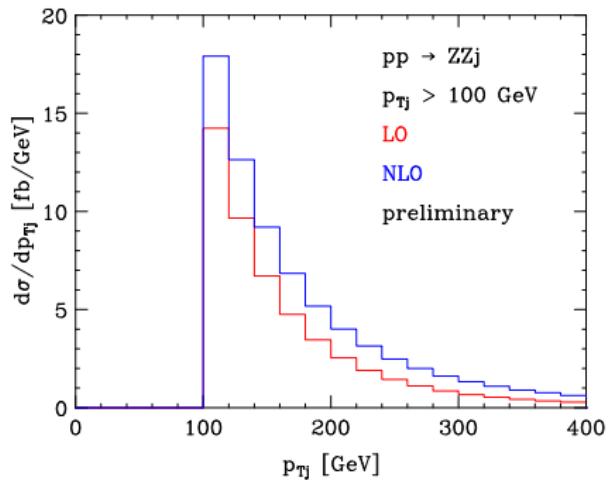
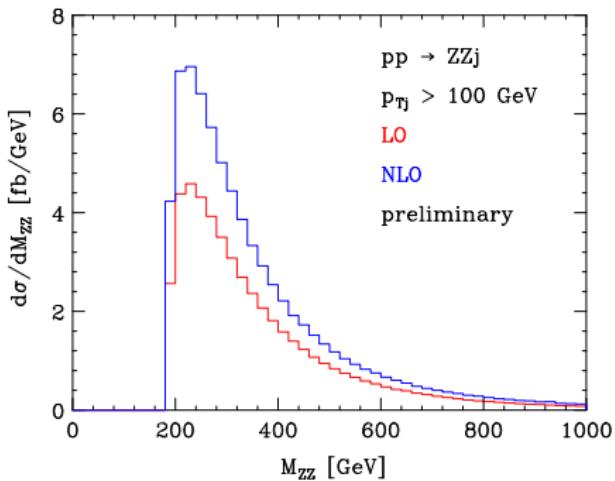
$\sigma(pp \rightarrow ZZj) [\text{fb}] \text{ at } \sqrt{s} = 14 \text{ TeV}$			
$\mu = \mu_R = \mu_F$	$M_Z/2$	M_Z	$2M_Z$
LO	1156(1)	1006(1)	874(1)
NLO: Born+virt	836(4)	899(4)	909(4)
NLO: vsub	603(1)	176(1)	79.5(4)
NLO: real	520(9)	407(7)	323(5)
NLO: complete	1959(14)	1482(12)	1312(9)

→ still large scale dependence at NLO (qg subprocesses)

$p_{T,\text{jet}} > 100 \text{ GeV}$, k_T jet algorithm ($R = 0.7$); sub: $\alpha_{\text{cut}} = 0.2$

Distributions

$Z Z$ invariant mass and $p_{T,jet}$ distributions



Normalising weak boson pair production at the LHC

Complementary to higher order corrections: *Extrapolate from LHC data!*

$$\sigma^B \approx \underbrace{\left(\frac{\sigma_{\text{theoretical}}^B}{\sigma_{\text{theoretical}}^A} \right)}_{\text{low uncertainty}} \cdot \underbrace{\sigma_{\text{measured}}^A}_{\text{low uncertainty}}$$

process $B: pp \rightarrow VV$ (NLO+gg), process $A: pp \rightarrow \ell^-\ell^+$ (DY at NLO)

parton level study: Campbell, Castaneda-Miranda, Fang, NK, Mellado, Sau Lan Wu

Advantage: correlated dependencies (on scales, PDFs, ...) will be mitigated
→ reduced uncertainty; eliminates luminosity uncertainty if applied to rates

G. Dissertori: *Try to make as many cross checks involving theoretical predictions and LHC data as possible to comprehensively validate our understanding!*

Results for $(ZZ \rightarrow 4\ell)/\text{DY}$

Cuts: $p_{T\ell} > 20 \text{ GeV}$, $|\eta_\ell| < 2.5$, $71 \text{ GeV} < M_{\ell\ell} < 111 \text{ GeV}$, $\Delta R_{\ell\ell} > 0.2$, $\Delta R_{\ell j} > 0.7$

Central scale choice: $\mu_0 = M_Z$, independent variation $\mu_R, \mu_F \in [\mu_0/4, 4\mu_0]$

LHC (14 TeV) cross sections [fb] and ratio for central scale

$M_{\text{all } \ell}$ range [GeV]	$\sigma_{pp \rightarrow 2\ell}^{NLO}$ (DY)	$\sigma_{pp \rightarrow ZZ \rightarrow 4\ell}^{NLO}$	$\sigma_{gg \rightarrow ZZ \rightarrow 4\ell}^{(LO)}$	$\frac{\sigma_{ZZ}}{\sigma_{\text{DY}}} \cdot 10^3$
200 - 250	886.8	4.00	0.591	5.17
250 - 300	376.6	1.82	0.265	5.54
300 - 350	186.2	0.93	0.123	5.66
350 - 400	102.8	0.53	0.066	5.83
400 - 450	60.5	0.32	0.041	5.94
450 - 500	38.0	0.20	0.027	6.01
500 - 750	71.9	0.37	0.057	5.92
750 - 1000	13.7	0.08	0.016	6.88

$\sigma(gg \rightarrow ZZ)/\sigma(pp \rightarrow ZZ, \text{NLO}) : 13\% - 17\%$, ratio fairly stable

Scale uncertainty reduction for $(ZZ \rightarrow 4\ell)/DY$

LHC (14 TeV) extreme cross sections [fb] and ratios with scale variation

and deviations from central value [%]

$M_{all\ \ell}$ range [GeV]	$\sigma_{pp \rightarrow 2\ell}^{NLO}$ (DY)	$\sigma_{pp \rightarrow ZZ \rightarrow 4\ell}^{NLO}$	$\sigma_{gg \rightarrow ZZ \rightarrow 4\ell}^{(LO)}$		$\frac{\sigma_{ZZ}}{\sigma_{DY}} \cdot 10^3$	
200 - 250 (max)	929.4	+4.8%	4.17	4.3	0.96	62.0
200 - 250 (min)	793.4	-10.5%	3.57	-10.6	0.38	-36.4
250 - 300	396.0	5.2	1.93	5.9	0.42	57.3
	341.9	-9.2	1.66	-9.0	0.18	-33.9
300 - 350	195.2	4.9	0.98	5.5	0.20	60.0
	170.4	-8.5	0.85	-8.5	0.08	-34.5
350 - 400	108.5	5.6	0.55	3.4	0.11	64.1
	97.7	-5.0	0.48	-10.0	0.04	-36.2
400 - 450	63.5	5.0	0.35	10.6	0.07	70.3
	57.4	-5.1	0.30	-6.4	0.03	-36.7
450 - 500	40.6	6.7	0.22	11.0	0.05	72.5
	36.2	-4.8	0.19	-6.0	0.02	-38.5
500 - 750	75.8	5.4	0.41	11.5	0.10	82.8
	70.1	-2.6	0.34	-8.9	0.03	-39.9
750 - 1000	14.9	8.7	0.08	8.2	0.03	96.3
	13.6	-0.5	0.07	-8.1	0.01	-44.2

Scale choice dependence of observables

Investigate if “rules of thumb” can be found for

- ▶ optimal scale choice at LO, NLO for given process and observable [1]
- ▶ Are scale-based uncertainty estimates compatible with higher-order corrections/data? Appropriate variation: 1/2 to 2 or 1/4 to 4 etc.?
- ▶ estimate NLO corrections for processes where programs are not yet available [2]

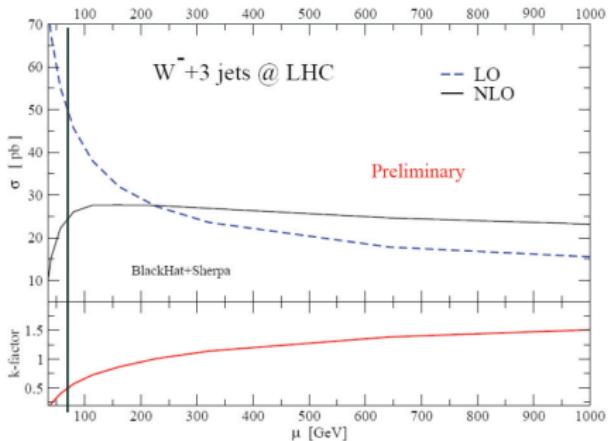
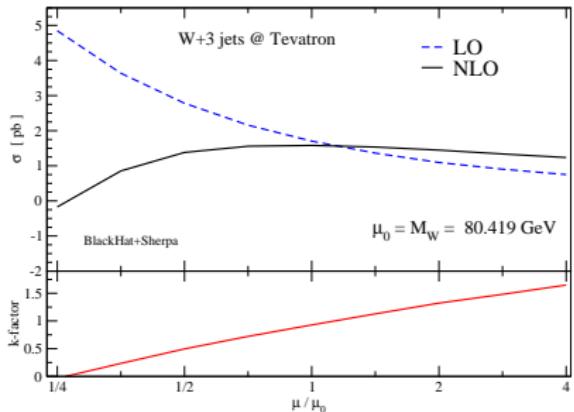
Interested: J. Huston [1,2], N. K. [1,2], G. Zanderighi [1], T. Gleisberg [1], ...

Multi-scale processes: Is average or sum the more appropriate scale choice?

For LHC processes like $V + \text{jets}$, $VV + \text{jets}$, $t\bar{t} + \text{jets}$: Comparison of NLO and LO predictions for relevant cross sections and distributions calculated with different scale choices in order to understand what choices are more appropriate and lead to reliable uncertainty estimates; using knowledge of existing NLO calculations to understand motivated scale choices at LO for uncalculated (to NLO) cross sections.

Scale dependence of $\sigma(W + 3 \text{ jets})$

Ellis, Giele, Kunszt, Melnikov, Zanderighi; Berger, Bern, Dixon, Febres Cordero, Forde,
Gleisberg, Ita, Kosower, Maitre (BlackHat & Sherpa)



Compare scale choices for LHC:

$$\mu_0 = M_W \quad \text{versus} \quad \mu_0 = H_T = E_{T\ell} + \cancel{E}_T + \sum_i E_{Tj,i}$$

Standardisation of NLO computations

Modular structure of NLO calculations

$$\begin{aligned}\sigma &= \sigma_{LO} + \sigma_{NLO} \\ \sigma_{LO} &= \int dPS_N \frac{1}{2s} |\mathcal{A}_{LO}|^2 \\ \sigma_{NLO} &= \int dPS_N \frac{\alpha_s}{2s} \left[\sum_j \int dPS_j \mathcal{D}_j + \mathcal{A}_{LO} \mathcal{A}_{NLO,V}^* + \mathcal{A}_{LO}^* \mathcal{A}_{NLO,V} \right] \\ &\quad + \int dPS_{N+1} \frac{\alpha_s}{2s} \left[|\mathcal{M}_{NLO,R}|^2 - \sum_j \mathcal{D}_j \right]\end{aligned}$$

- ▶ proposal concerns the **virtual** term
- ▶ **infrared (IR) subtraction** method not fixed
 - might need flexibility to add parton shower

Les Houches accord on standardisation of NLO computations

Les Houches discussions on standard interface
to combine **real (R)** and **virtual (V)** contributions

Binoth, Dittmaier, Gleisberg, Heinrich, NK, Kosower, Maitre, Maltoni, Reiter, Passarino, Skands, ...



A draft for based on the BlackHat-Sherpa implementation
can be found at

<http://www.lpthe.jussieu.fr/LesHouches09Wiki/index.php/Draft>

Further steps:

- ▶ checking proposal by applying and testing it → D. Maitre, T. Gleisberg
- ▶ compiling email list and **communicating proposal to one-loop/MC community**
- ▶ preparing write-up with examples for Les Houches proceedings

Defining the virtual component

The following information is sufficient to define the virtual component of electroweak (EW) and QCD NLO computations:

- ▶ Model parameters (passed using the Les Houches accord format for model parameters)
- ▶ Electroweak/QCD regularisation, renormalisation scheme
 - ▶ QCD: 't Hooft-Veltman, DR, FDH, $\overline{\text{MS}}$, ...
 - ▶ EW: many different variants are used
 - NLO provider has to pass appropriate information (e.g. $\alpha(M_Z)$ vs. $\alpha(0)$, complex mass scheme, etc.)
- ▶ additional specifications and/or approximations of the calculation, e.g.
 - ▶ leading colour
 - ▶ $m_b = 0$
 - ▶ ...

In an actual implementation, this information can be exchanged during initialisation.

Calling the information of the virtual amplitude

- ▶ One-loop information in LO-NLO amplitude interference term
- ▶ contains IR divergences regulated by dimensional regularization ($d = 4 - 2\epsilon$).
- ▶ After initialisation the full information for the virtual NLO correction can be requested **event by event** from the one-loop engine

$$(p_x, p_y, p_z, E, M, \mu, \alpha_s(\mu), \alpha(0)) \rightarrow \text{Const}(\epsilon) \left(\frac{\text{CoeffPole2}}{\epsilon^2} + \frac{\text{CoeffPole1}}{\epsilon} + \text{CoeffPole0} \right),$$

$|\mathcal{M}_{\text{Born}}|^2$ and optional additional information

- ▶ minimal information: colour and helicity summed term
- ▶ more information on helicity and/or colour may be provided optionally by the one-loop provider
- ▶ framework usable for cases with no tree amplitudes
- ▶ proposal independent from specific IR subtraction procedure

Summary

- ▶ Experimental TeV scale physics exploration will start soon
- ▶ Need solid theoretical predictions for signals and backgrounds
- ▶ VV (+ jets) production: important background
→ higher order corrections required (and becoming available)
- ▶ Combining theory predictions and LHC data allows to improve predictions as well as validation/cross checks
- ▶ Qualitative understanding of best scale choice?
- ▶ Automation and standardisation is helpful