Normalising weak boson pair production with LHC data

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- Normalising weak boson pair production at the LHC
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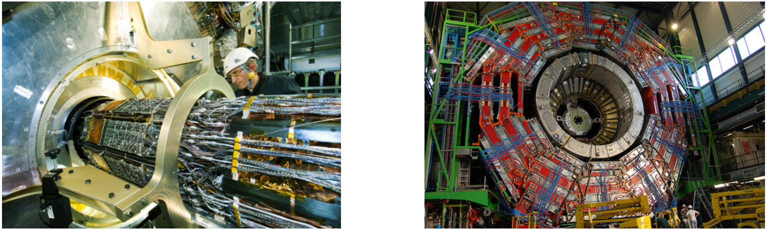
The Large Hadron Collider (re)starts ... *soon*

Protons colliding at 14 Tera-eV ≈ 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 ⟶ 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

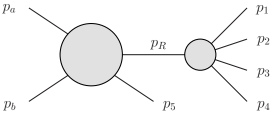
S = nr. of signal events, B = nr. of background events,

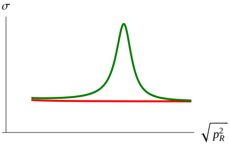
Observation significance: $\sigma = S/\sqrt{B+S}$

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

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

The experimentally ideal case: a new, reconstructible mass peak





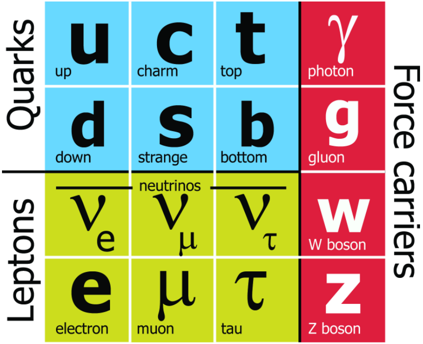
p_1, p_2, p_3, p_4 measurable $\longrightarrow$ $p_R = p_1 + p_2 + p_3 + p_4$

⟶ invariant mass distribution from experimental data (⟶ resonance mass and width)

⟶ background via sideband interpolation (⟶ signal)

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

Weak bosons in the Standard Model



Poincare-invariant, renormalisable quantum field theory (QFT)

with local gauge invariance $SU(3) \times SU(2)_L \times U(1)$

→ vector bosons g, $\boldsymbol{W}^{\pm}$, $\boldsymbol{Z}$, 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:

$\mathcal{L} = -\frac{1}{2} F_{\mu\nu} F^{\mu\nu}$ 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 $m\overline{\psi}\psi = m\overline{\psi}_L \psi_R + m\overline{\psi}_R \psi_L$ 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

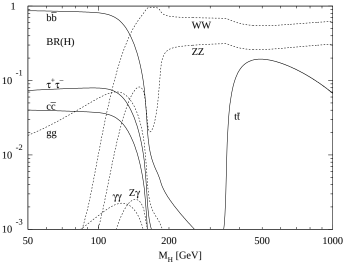
Weak bosons: importance for LHC physics

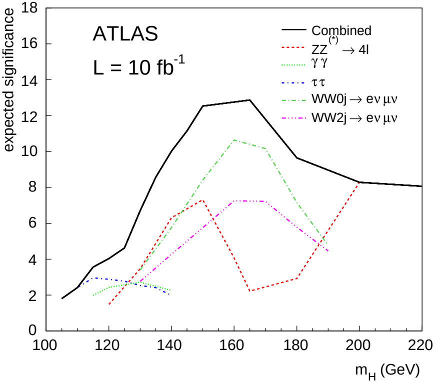
LHC search for New Physics (SUSY, ...)

- dark matter candidate → signatures with $\not{E}_T$
- cascade decays with new EW gauge bosons/gauginos → $\ell^\mp$
- cascade decays of new coloured particles → jets

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

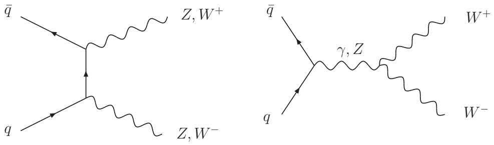
LHC search for SM & BSM Higgs





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

Theoretical predictions for weak boson pair production



- $e^+e^-, pp, p\bar{p} \rightarrow WW, ZZ$ 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]

- $pp, p\bar{p} \rightarrow WW, ZZ, WZ$ 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]

- $gg \to WW, ZZ$ (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); Binoth, Ciccolini, NK, Krämer (2005, 2006); Binoth, NK, Mertsch (2008)

- 2-loop-virtual–Born interference for $q\bar{q} \to WW \longrightarrow$ NNLO QCD correction

Chachamis, Czakon, Eiras (2008)

Predictions for weak boson pair + jets production

- $pp, p\bar{p} \to WW$ + jet at NLO QCD (with leptonic decays)

Dittmaier, Kallweit, Uwer (2007, 2009); Campbell, K. Ellis, Zanderighi (2007)

- $pp, p\bar{p} \to ZZ$ + jet at NLO QCD

Binoth, Gleisberg, Karg, NK, Sanguinetti (2009)

- Weak boson fusion contribution to $pp \to WW$ + 2 jets, ZZ + 2 jets, WZ + 2 jets at NLO QCD with leptonic decays

B. Jäger, Oleari, Zeppenfeld (2006); Bozzi, B. Jäger, Oleari, Zeppenfeld (2007)

WW signal and background cross sections at the LHC

	$\sigma(pp \to W^*W^* \to \ell\bar\nu\bar\ell'\nu')$ [fb], $\sqrt{s} = 14$ TeV, $M_W/2 \le \mu \le 2M_W$				
	$q\bar q$		gg	$\frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}}$	$\frac{\sigma_{\mathrm{NLO}+gg}}{\sigma_{\mathrm{NLO}}}$
	LO	NLO	NNLO		
σ_{tot}	$875.8(1)^{+6\%}_{-8\%}$	$1373(1)^{+5\%}_{-6\%}$	$60.00(1)^{+26\%}_{-20\%}$	1.57	1.04
σ_{std}	$270.5(1)^{+7\%}_{-9\%}$	$491.8(1)^{+6\%}_{-7\%}$	$29.79(2)^{+26\%}_{-20\%}$	1.82	1.06
σ_{bkg}	$4.583(2)^{+9\%}_{-10\%}$	$4.79(3)^{+0.2\%}_{-3\%}$	$1.4153(3)^{+29\%}_{-22\%}$	1.05	1.30

LO, NLO: MCFM Campbell, K. Ellis (1999), gg: GG2WW Binoth, Ciccolini, NK, Krämer (2005, 2006)

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

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

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

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

ZZ cross sections at the LHC

	$\sigma(pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}')$ [fb], $\sqrt{s} = 14$ TeV				
	$q\bar{q}$		gg	$\frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}}$	$\frac{\sigma_{\mathrm{NLO}+gg}}{\sigma_{\mathrm{NLO}}}$
	LO	NLO	NNLO		
σ_{min}	$105.2(1)$	$118.9(2)$	$16.3(1)$	1.13	1.14
σ_{std}	$7.343(1)$	$10.953(2)$	$1.492(2)$	1.49	1.14

minimal cuts: $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV

standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 75 GeV $< M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} < 105$ GeV

scale uncertainty $M_Z/2 \le \mu \le 2M_Z$: NLO: 4%, gg: 20%

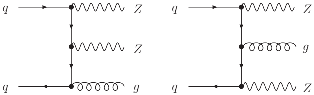
LO, NLO: MCFM Campbell, K. Ellis (1999), gg: GG2ZZ Binoth, NK, Mertsch (2008)

NLO QCD calculation for ZZ + jet

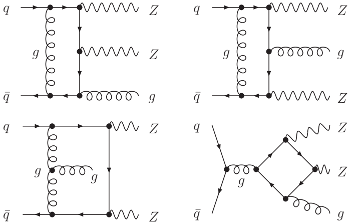
$pp \to ZZ$ + jet @ NLO is component of $pp \to ZZ$ @ NNLO

6 subprocesses: $q\bar{q} \to ZZg,\;\; qg \to ZZq,\;\; \bar{q}g \to ZZ\bar{q}$ with $q = u, d$

LO amplitude contributions



Virtual corrections contributions



Real corrections: crossings of $0 \to ZZq\bar{q}gg$ and $0 \to ZZq\bar{q}q'\bar{q}'$

NLO QCD calculation for ZZ + 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

$2 \to 3$ status: complete and cross checked at amplitude level

Real correction: Catani-Seymour dipole subtraction

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

$p_1 p_2 \to ZZ p_3 p_4$: 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) + MadDipole Frederix, Gehrmann, Greiner (2008); 2nd cross check: Helac dipoles Czakon, Papadopoulos, Worek (2009) ✓

$2 \to 4$ status: complete, 9 digit agreement for $|\mathcal{M}_R|^2$ and all dipoles ✓

ZZ + jet results

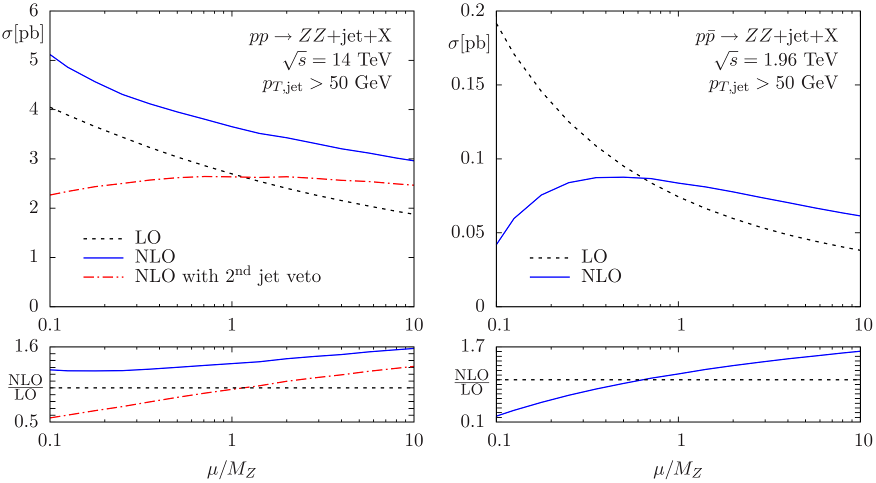
LHC	$\sigma(pp \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 14$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	$6.500(6)$	$2.696(2)^{+13\%}_{-11\%}$	$1.0057(9)$	$0.2297(2)$
NLO	$8.01(3)$	$3.653(9)^{+8\%}_{-6\%}$	$1.511(4)$	$0.415(2)$
NLO with 2^{nd} jet veto		$2.637(9)^{+0.2\%}_{-1\%}$	$0.755(4)$	$0.1005(9)$

Tevatron	$\sigma(p\bar{p} \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 1.96$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	$0.2722(1)$	$0.07441(6)^{+28\%}_{-20\%}$	$0.016025(7)$	$0.0012648(6)$
NLO	$0.3307(6)$	$0.0836(1)^{+5\%}_{-7\%}$	$0.01583(4)$	$0.000976(4)$

rel. deviation with $\frac{M_Z}{2} < \mu < 2M_Z$ for $p_{T,\text{jet}}$ cut = 50 GeV; 2^{nd} jet veto: $p_{T,\text{jet}} > 50$ GeV

Details: $N_F = 5$ (u, c, d, s, b), $M_q = 0$ (including: M_b = 0), $M_Z = 91.188$ GeV, $\alpha(M_Z) = 0.00755391226$, $\sin^2\theta_W = 0.222247$, LO PDF: CTEQ6L1, NLO PDF: CTEQ6M Pumplin et al. (2002), $\alpha_s(M_Z)$ from LHAPDF, CTEQ6L1: $\alpha_s(91.188\text{ GeV}) = 0.129783$ [LO running], CTEQ6M: $\alpha_s(91.70\text{ GeV}) = 0.1179$ [NLO running], jet definition: k_T algorithm ($\Delta R = 0.7$); $\alpha_{\text{cut}} = 0.2$, central scale: $\mu_R = \mu_F = M_Z$, $\mu_i = 2^{i/2} M_Z$ with $i \in \mathbb{Z}$

Scale variation for LHC and Tevatron



$\mu = \mu_R = \mu_F$, 2^{nd} jet veto: $p_{T,\text{jet}} > 50$ GeV

Scale uncertainty for LHC and Tevatron

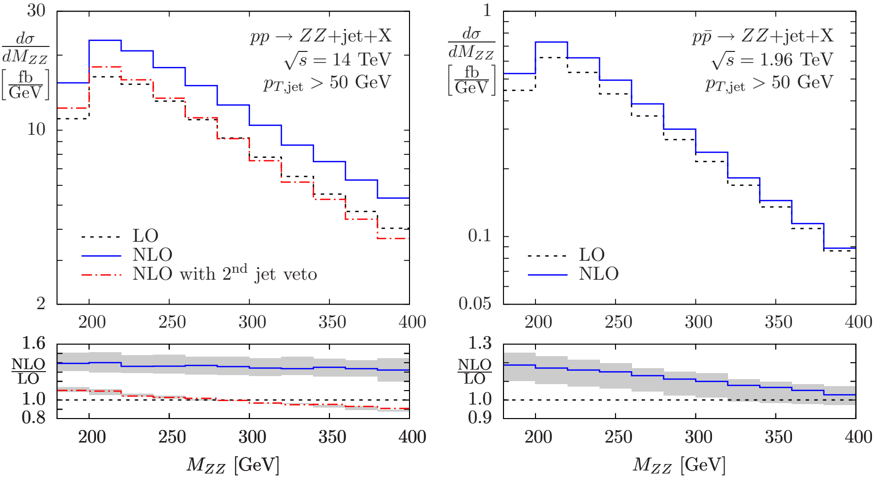
LHC

	$\Delta\sigma/\sigma(pp \to ZZ + \text{jet})$, $\sqrt{s} = 14$ TeV		
	$\mu/M_Z \in [\frac{1}{2}, 2]$	$\mu/M_Z \in [\frac{1}{4}, 4]$	$\mu/M_Z \in [\frac{1}{8}, 8]$
LO	12%	23%	34%
NLO	7%	15%	23%
NLO with 2^{nd} jet veto	0.5%	3%	6%

Tevatron

	$\Delta\sigma/\sigma(p\bar{p} \to ZZ + \text{jet})$, $\sqrt{s} = 1.96$ TeV		
	$\mu/M_Z \in [\frac{1}{2}, 2]$	$\mu/M_Z \in [\frac{1}{4}, 4]$	$\mu/M_Z \in [\frac{1}{8}, 8]$
LO	23%	44%	62%
NLO	6%	11%	19%

ZZ invariant mass distribution for LHC and Tevatron



K-factor bands: $M_Z/2 < \mu < 2M_Z$ variation for σ_{NLO} only, $\sigma_{\text{LO}}(M_Z)$

Normalising weak boson pair production at the LHC

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

Complementary to higher order corrections:

Extrapolate from LHC data!

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

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

$\boxed{\text{process } B\text{: } pp \to VV \text{ (NLO+}gg\text{)}, \quad \text{process } A\text{: } pp \to \ell^-\ell^+ \text{ (DY at NLO)}}$

Drell-Yan "SM candle":

experimental stat. uncertainty: $\boxed{0.15\% \text{ with } 1 \text{ fb}^{-1}}$, $\boxed{\text{residual scale uncertainty} < 1\%}$

NNLO QCD corrections: Hamberg, van Neerven, Matsuura (1991); Harlander, Kilgore (2002); Melnikov, Petriello (2006); Catani, Cieri, Ferrera, de Florian, Grazzini (2009)

NLO QED/EW corrections: Baur, Brein, Hollik, Schappacher, Wackeroth (2001); Zykunov (2007); Carloni Calame, Montagna, Nicrosini, Vicini (2007)

Results for $(ZZ \to 4\ell)$/DY

Cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 71 GeV $< M_{\ell\ell} < 111$ 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]	$\sigma^{NLO}_{pp\to 2\ell}$ (DY)	$\sigma^{NLO}_{pp\to ZZ\to 4\ell}$	$\sigma^{(LO)}_{gg\to ZZ\to 4\ell}$	$\frac{\sigma_{ZZ}}{\sigma_{DY}} \cdot 10^3$
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

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

[experimental uncertainties (e.g. lepton identification and isolation efficiencies) not yet taken into account, since parton level only]

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

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

and deviations from central value [%]

$M_{\text{all } \ell}$ range [GeV]	$\sigma^{NLO}_{pp\to 2\ell}$ (DY)		$\sigma^{NLO}_{pp\to ZZ\to 4\ell}$		$\sigma^{(LO)}_{gg\to ZZ\to 4\ell}$		$\frac{\sigma_{ZZ}}{\sigma_{DY}} \cdot 10^3$	
200 - 250 (max)	929.4	+4.8%	4.17	4.3	0.96	62.0	5.52	6.6
200 - 250 (min)	793.4	−10.5%	3.57	-10.6	0.38	-36.4	4.98	-3.8
250 - 300	396.0	5.2	1.93	5.9	0.42	57.3	6.06	9.3
	341.9	-9.2	1.66	-9.0	0.18	-33.9	5.32	-4.1
300 - 350	195.2	4.9	0.98	5.5	0.20	60.0	6.15	8.7
	170.4	-8.5	0.85	-8.5	0.08	-34.5	5.45	-3.8
350 - 400	108.5	5.6	0.55	3.4	0.11	64.1	6.08	4.3
	97.7	-5.0	0.48	-10.0	0.04	-36.2	5.35	-8.3
400 - 450	63.5	5.0	0.35	10.6	0.07	70.3	6.65	11.8
	57.4	-5.1	0.30	-6.4	0.03	-36.7	5.47	-8.0
450 - 500	40.6	6.7	0.22	11.0	0.05	72.5	6.66	10.9
	36.2	-4.8	0.19	-6.0	0.02	-38.5	5.72	-4.7
500 - 750	75.8	5.4	0.41	11.5	0.10	82.8	6.80	14.8
	70.1	-2.6	0.34	-8.9	0.03	-39.9	5.29	-10.7
750 - 1000	14.9	8.7	0.08	8.2	0.03	96.3	7.81	13.5
	13.6	-0.5	0.07	-8.1	0.01	-44.2	5.93	-13.8

LHC collision energy dependence for $(ZZ \to 4\ell)$/DY

ratio $\frac{\sigma_{pp\to ZZ\to 4\ell}}{\sigma_{pp\to 2\ell}} \cdot 10^3$ for different $M_{\text{all }\ell}$ ranges [GeV]

$\sqrt{s}$	200-250	250-300	300-500	500-1000
14	5.17	5.54	5.79	6.08
10	4.98	5.33	5.48	5.61
8	4.92	5.24	5.34	5.53

ratio deviations $< 10\%$

Results for W boson pairs at the LHC (14 TeV)

Cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{E}_T > 20$ GeV, $\Delta R_{\ell\ell} > 0.2$, $\Delta R_{\ell j} > 0.7$, $\mu_0 = M_W$

$$(WW \to \ell\nu\ell\nu)/(pp \to \ell^+\ell^-)$$

	$\sigma^{NLO}_{q\bar{q}\to Z}$	$\sigma^{NLO}_{q\bar{q}\to Z^*}$	$\sigma^{NLO}_{q\bar{q}\to WW}$	$\sigma^{LO}_{gg\to WW}$	$\frac{\sigma_{WW}}{\sigma_Z}\cdot 10^3$	$\frac{\sigma_{WW}}{\sigma_{Z^*}}$
Nom.	785.3 pb	2256.4 fb	636.0 fb	31.04 fb	0.85	0.296
Max.	6.2	4.6	11.5	62.1	16.1%	9.4%
Min.	-15.7	-9.9	-13.4	-36.0	-8.4%	-5.3%

$\sigma_{q\bar{q}\to Z}$: 71 GeV $< M_{\ell\ell} < 111$ GeV, $\sigma^{NLO}_{q\bar{q}\to Z^*}$: $M_{\ell\ell} > 185$ GeV

$$(ZZ \to 4\ell)/(WW \to \ell\nu\ell\nu)$$

σ_{WW}	$\delta\sigma_{WW}$	σ_{ZZ}	$\delta\sigma_{ZZ}$	$\frac{\sigma_{ZZ}}{\sigma_{WW}}\cdot 10^2$	$\delta\frac{\sigma_{ZZ}}{\sigma_{WW}}$
667.0 fb	13.9% -14.4%	11.51 fb	10.9% -13.1%	1.73	1.6% -2.6%

$\sqrt{s}$ variation $\longrightarrow$ ratio deviations $< 5\%$, scale uncertainties similar

Summary

- Experimental TeV scale physics exploration will start soon
- Need solid theoretical predictions for signals and backgrounds
- VV (+ jets) production: important background
  $\longrightarrow$ higher order corrections required (and becoming available)
- Combining theory predictions and LHC data allows
  to improve predictions as well as validation/cross checks
- Comparison with data will help to improve assessment of systematic theoretical uncertainties (scale choice/variation)

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