W and Z boson production at the LHC

Nikolas Kauer
Royal Holloway, University of London

ZZ+jet research in collaboration with
Jennifer Archibald, Thomas Binoth, Tanju Gleisberg, Stefan Karg, Grégory Sanguinetti

Particle Physics Seminar
Rutherford Appleton Laboratory
October 20, 2010

Outline

- Introduction
- Weak bosons: importance for LHC physics
- Theoretical predictions for weak boson production
- NLO QCD calculation for ZZ + jet
- NLO QCD results for W + jets and Z + jets
- Data-driven estimation methods
- Conclusions

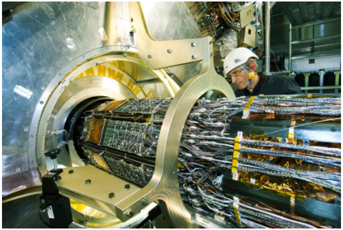
The Large Hadron Collider is collecting Terascale data

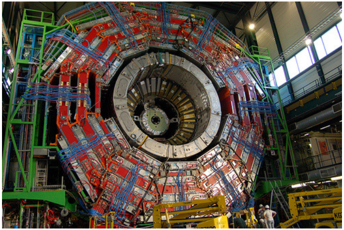
Protons colliding at 7 Tera-eV $\approx$ 7500 $M_p\, c^2 \sim 10^{-6}$ J total energy (eventually 14 TeV)

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 $\approx$ 1 ton of copper, collisions at 40 MHz $\longrightarrow$ 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

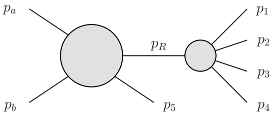
S = nr. of signal events, B = nr. of background events,

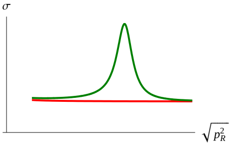
Observation significance: $\sigma = S/\sqrt{B+S}$

Discovery if $\sigma \geq 5$ ⟶ P(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





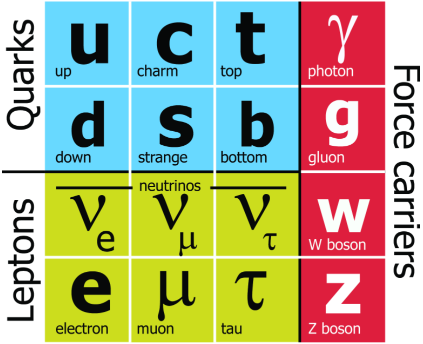
p_1, p_2, p_3, p_4 measurable ⟶ $p_R = p_1 + p_2 + p_3 + p_4$

⟶ 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 $SU(3) \times SU(2)_L \times U(1)$

$\longrightarrow$ vector bosons g, $\boldsymbol{W^\pm}$, $\boldsymbol{Z}$, γ

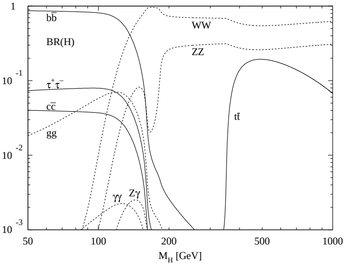
Weak bosons: importance for LHC physics

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

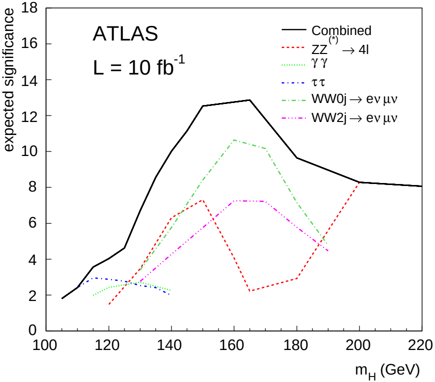
- dark matter candidate ⟶ signatures with $\not{E}_T$
- cascade decays with new EW gauge bosons/gauginos ⟶ $\ell^\mp$
- cascade decays of new coloured particles ⟶ jets

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

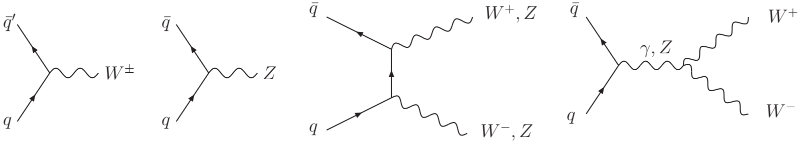
LHC search for SM & BSM Higgs



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



A brief history of theoretical predictions for weak boson production at hadron colliders



- $pp, p\bar{p} \to W, Z$ at LO (and decays and $n \leq 4$ additional jets)

Quigg (1977); Peierls, Trueman, Wang (1977); Kleiss, Stirling (1985); Ellis, Kleiss, Stirling (1985); Berends, Giele, Kleiss, Kuijf, Stirling (1989); Mangano, Parke (1990); Berends, Giele, Kuijf, Tausk (1991)

Modern LO Monte Carlo tools:

ALPGEN, CompHEP/CalcHEP, Helac-Phegas, MadGraph/MadEvent, Sherpa

decays and $n \leq 6$ additional jets

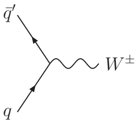
A brief history of theoretical predictions for weak boson production at hadron colliders

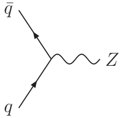
- $pp, p\bar{p} \to W, Z$ at NLO QCD (and decays and $n \leq 3$ additional jets)

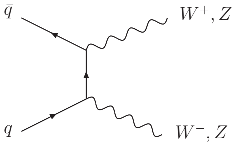
$n = 0$: Altarelli, K. Ellis, Martinelli (1979); Kubar-Andre , Paige (1979); **$n = 1$:** K. Ellis, Martinelli, Petronzio (1983); Arnold, Reno (1989); Arnold, K. Ellis, Reno (1989); Giele, Glover, Kosower (1993); Giele, Keller, Laenen (1996); Campbell, K. Ellis, F. Maltoni, Willenbrock (2004); **$n = 2$:** Campbell, K. Ellis (2002); Campbell, K. Ellis, Rainwater (2003); Oleari, Zeppenfeld (2004); Campbell, K. Ellis, F. Maltoni, Willenbrock (2006, 2007, 2008); Febres Cordero, Reina, Wackeroth (2006, 2008, 2009); **$n = 3$:** K. Ellis, Melnikov, Zanderighi (2009); C.F. Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre (2009, 2010);

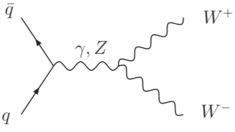
$W + 4$ jets: C.F. Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre (2011)

A brief history of theoretical predictions for weak boson production at hadron colliders









- $pp, p\bar{p} \to WW, ZZ$ at LO (and decays)

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

- $pp, p\bar{p} \to WW, ZZ, WZ$ 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) [$pp, p\bar{p} \to \ell\bar{\ell}\ell'\bar{\ell}'$ at NLO QCD]

A brief history of theoretical predictions for weak boson production at hadron colliders

- $gg \to WW, ZZ$ (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)

- $pp, p\bar{p} \to WW, ZZ$ + 1 jet at NLO QCD (with leptonic decays)

Dittmaier, Kallweit, Uwer (2007); Campbell, K. Ellis, Zanderighi (2007); Binoth, Gleisberg, Karg, NK, Sanguinetti (2009)

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

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

Updated experimenter's wishlist for LHC processes

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi. ZZjet completed by Binoth/Gleisberg/Karg/NK/Sanguinetti.
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld (see also Binoth/Ossola/Papadopoulos/Pittau)
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa and Rocket collaborations

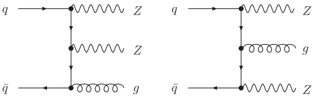
NLO QCD calculation for ZZ + jet

H/NP background, ZZ+jet @ NLO: component of ZZ @ NNLO, anomalous couplings searches

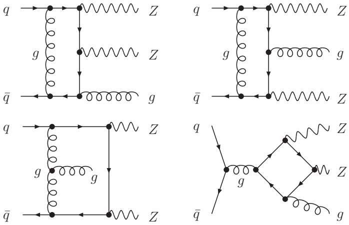
(no $ZZ\gamma$ or ZZZ coupling in SM)

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

LO amplitude contributions



Virtual corrections contributions



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

Calculational details

Archibald, Binoth, Gleisberg, Karg, NK, 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

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 and cross checked (9 digit agreement for $|\mathcal{M}_R|^2$ and all dipoles)

Tuned comparison with DKU's calculation

T. Binoth, T. Gleisberg, S. Karg, NK, G. Sanguinetti and S. Dittmaier, S. Kallweit, P. Uwer

Compare results for one phase space (PS) point and PS-integrated results.

Exactly the same setup is required!

Selected PS configuration: four-momenta $p = (E, p_x, p_y, p_z)$ [GeV] with $1, 2 \rightarrow 3, 4, 5$:

$$p_1^\mu = (250, 0, 0, 250), \qquad p_2^\mu = (250, 0, 0, -250),$$
$$p_3^\mu = (125.9335600344245, -81.91900733932759, -15.22986911133704, -24.52218428963296),$$
$$p_4^\mu = (201.2131630027446, 37.57875773939030, -105.1640094872687, 140.3561672919824),$$
$$p_5^\mu = (172.8532769628309, 44.34024959993729, 120.3938785986057, -115.8339830023494),$$

Complete specification of results:

The following results essentially employ the setup of Binoth et al. The CTEQ6 set of parton distribution functions (PDFs) is used throughout, i.e. CTEQ6L1 PDFs with a 1-loop running α_s are taken in LO and CTEQ6M PDFs with a 2-loop running α_s in NLO. In the strong coupling constant the number of active flavours is $N_\mathrm{f} = 5$, and we use the default LHAPDF values leading to $\alpha_\mathrm{s}^\mathrm{LO}(91.188\ \mathrm{GeV}) = 0.129783$ and $\alpha_\mathrm{s}^\mathrm{NLO}(91.70\ \mathrm{GeV}) = 0.1179$. The top-quark loop in the gluon self-energy is subtracted at zero momentum. The running of α_s is, thus, generated solely by the contributions of the light quark and gluon loops. In all results shown in the following, the renormalization and factorization scales are set to M_Z. The top-quark mass is $m_t = 174.3$ GeV, the masses of all other quarks are neglected. The weak boson masses are $M_Z = 91.188$ GeV and $M_H = 150$ GeV. The weak mixing angle is set to its on-shell value, i.e. fixed by $s_w^2 = 0.222247$, and the electromagnetic coupling constant is set to $\alpha = 0.00755391226$. We apply the $k_\perp$ jet algorithm with covariant E-recombination scheme and $R = 0.7$ for the definition of the tagged hard jet and restrict the transverse momentum of the hardest jet by $p_{\mathrm{T,jet}} > 50$ GeV.

Comparison for single phase space point

	$\lvert\mathcal{M}_{\mathrm{LO}}\rvert^2/e^4/g_s^2\,[\mathrm{GeV}^{-2}]$
$u\bar{u} \to ZZg$	**(12-13 digit agreement)**
BGKKS	$9.081603376311467 \cdot 10^{-4}$
DKU	$9.081603376315696 \cdot 10^{-4}$
$d\bar{d} \to ZZg$	
BGKKS	$1.892589730735170 \cdot 10^{-3}$
DKU	$1.892589730736050 \cdot 10^{-3}$
$ug \to ZZu$	
BGKKS	$1.687614989680196 \cdot 10^{-4}$
DKU	$1.687614989680182 \cdot 10^{-4}$
$dg \to ZZd$	
BGKKS	$3.516959138773490 \cdot 10^{-4}$
DKU	$3.516959138773458 \cdot 10^{-4}$
$g\bar{u} \to ZZ\bar{u}$	
BGKKS	$1.319241114194492 \cdot 10^{-5}$
DKU	$1.319241114194495 \cdot 10^{-5}$
$g\bar{d} \to ZZ\bar{d}$	
BGKKS	$2.749274639763224 \cdot 10^{-5}$
DKU	$2.749274639763229 \cdot 10^{-5}$

Virtual corrections for single PS point

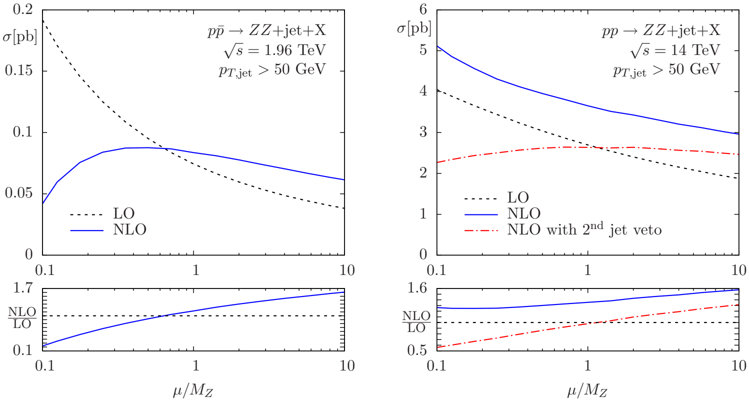
	$c_0^{\mathrm{bos}}\,[\mathrm{GeV}^{-2}]$	$c_0^{\mathrm{ferm}}\,[\mathrm{GeV}^{-2}]$
$u\bar{u} \to ZZg$		**(8-12 digit agreement)**
BGKKS	$2.571718370986939 \cdot 10^{-4}$	$2.771274006707126 \cdot 10^{-6}$
DKU	$2.571718370988091 \cdot 10^{-4}$	$2.771273991103833 \cdot 10^{-6}$
$d\bar{d} \to ZZg$		
BGKKS	$5.335637852921577 \cdot 10^{-3}$	$3.553804947755081 \cdot 10^{-6}$
DKU	$5.335637852923933 \cdot 10^{-3}$	$3.553804924505993 \cdot 10^{-6}$
$ug \to ZZu$		
BGKKS	$3.455303690923093 \cdot 10^{-4}$	$-1.575277709579237 \cdot 10^{-6}$
DKU	$3.455303690940059 \cdot 10^{-4}$	$-1.575277712403393 \cdot 10^{-6}$
$dg \to ZZd$		
BGKKS	$7.182218731401221 \cdot 10^{-4}$	$-2.134836868278616 \cdot 10^{-6}$
DKU	$7.182218731436469 \cdot 10^{-4}$	$-2.134836871947412 \cdot 10^{-6}$
$g\bar{u} \to ZZ\bar{u}$		
BGKKS	$7.284079447744509 \cdot 10^{-5}$	$-3.877856878313408 \cdot 10^{-6}$
DKU	$7.284079439746620 \cdot 10^{-5}$	$-3.877856878314387 \cdot 10^{-6}$
$g\bar{d} \to ZZ\bar{d}$		
BGKKS	$1.505448756089957 \cdot 10^{-5}$	$-4.839140375435081 \cdot 10^{-6}$
DKU	$1.505448754415003 \cdot 10^{-5}$	$-4.839140375436319 \cdot 10^{-6}$

Integrated cross section comparison

$pp \to ZZ$+jet+X @ LHC	σ_{LO}[fb]	σ_{NLO}[fb]	$\sigma_{\mathrm{NLO,excl}}$[fb]
BGKKS	$2697.82\,[42]$	$3644.5\,[3.0]$	$2627.5\,[3.0]$
DKU	$2697.81\,[18]$	$3644.6\,[1.0]$	$2626.3\,[1.1]$
$p\bar{p} \to ZZ$+jet+X @ Tevatron	σ_{LO}[fb]	σ_{NLO}[fb]	$\sigma_{\mathrm{NLO,excl}}$[fb]
BGKKS	$74.5589\,[90]$	$83.665\,[62]$	$78.824\,[62]$
DKU	$74.5664\,[76]$	$83.751\,[47]$	$78.915\,[47]$

good agreement within MC-integration errors

Results: ZZ + jet production at LO and NLO



Input parameters/settings:

$N_f = 5$ ($M_q = 0$ incl. $q = b$), $M_Z = 91.188$ GeV,

$\alpha(M_Z) = 0.00755391226$, $\sin^2\theta_W = 0.222247$

PDF: CTEQ6L1 (LO), CTEQ6M (NLO) Pumplin et al. (2002)

scale choice $\mu := \mu_R = \mu_F = M_Z$, incl. k_t algorithm ($R = 0.7$)

LO and NLO scale uncertainty

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%

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%

ZZj uncertainties deviate from WWj uncertainties (DKU) by less than 2%-points

$p_{T,\text{hardest jet}} > 50$ GeV, 2^{nd} jet veto: no additional jets with $p_T > 50$ GeV

$p_{T,\text{hardest jet}}$ cut dependence

Tevatron

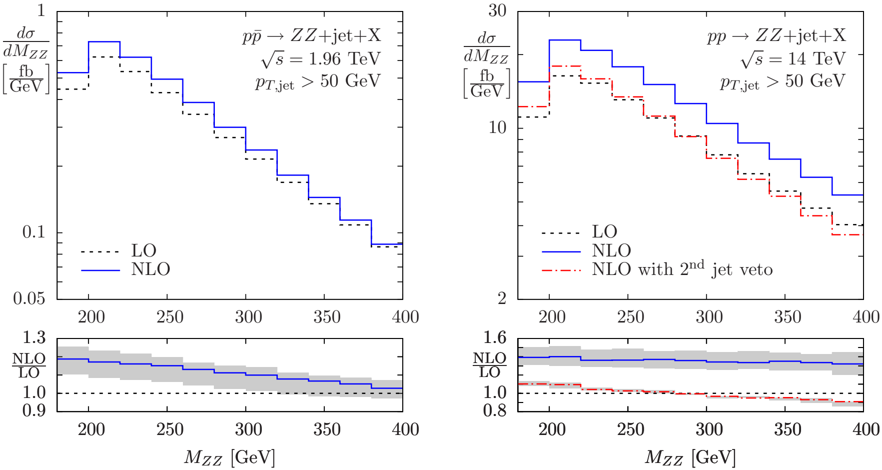
	$\sigma(p\bar{p} \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 1.96$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	$0.27202(3)$	$0.07456(1)^{+28\%}_{-20\%}$	$0.016037(2)$	$0.0012651(1)$
NLO	$0.3307(6)$	$0.0836(1)^{+5\%}_{-7\%}$	$0.01583(4)$	$0.000976(4)$

LHC

	$\sigma(pp \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 14$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	$6.505(1)$	$2.6978(4)^{+13\%}_{-11\%}$	$1.0066(1)$	$0.22974(3)$
NLO	$8.01(3)$	$3.653(9)^{+8\%}_{-6\%}$	$1.511(4)$	$0.415(2)$
NLO with 2^{nd} jet veto		$2.637(9)^{+0.2\%}_{-1\%}$	$0.755(4)$	$0.1005(9)$

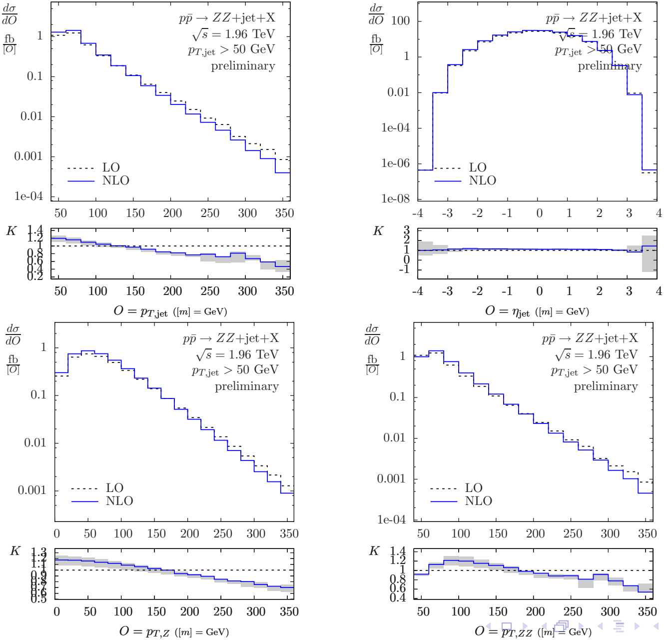
A sample differential distribution

ZZ invariant mass distribution at the Tevatron and LHC

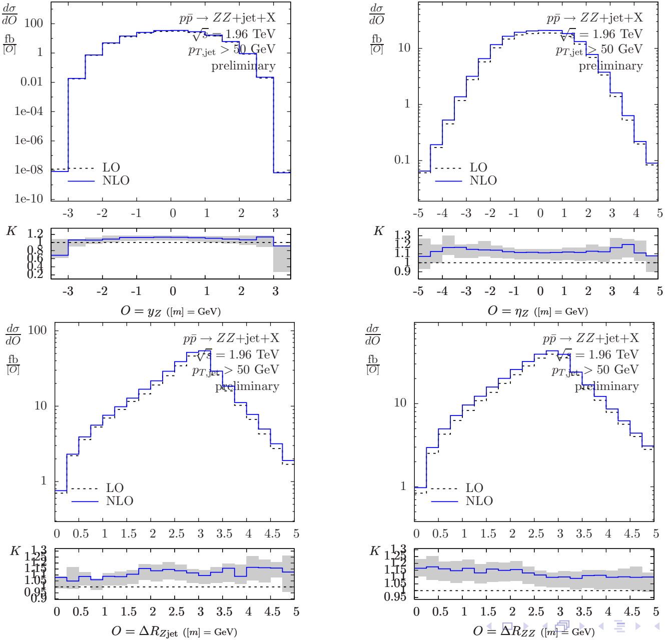


K-factor band: $[d\sigma_{\text{NLO}}/dM_{ZZ}](\mu)/[d\sigma_{\text{LO}}/dM_{ZZ}](M_Z)$ with $\mu/M_Z \in [\frac{1}{2}, 2]$

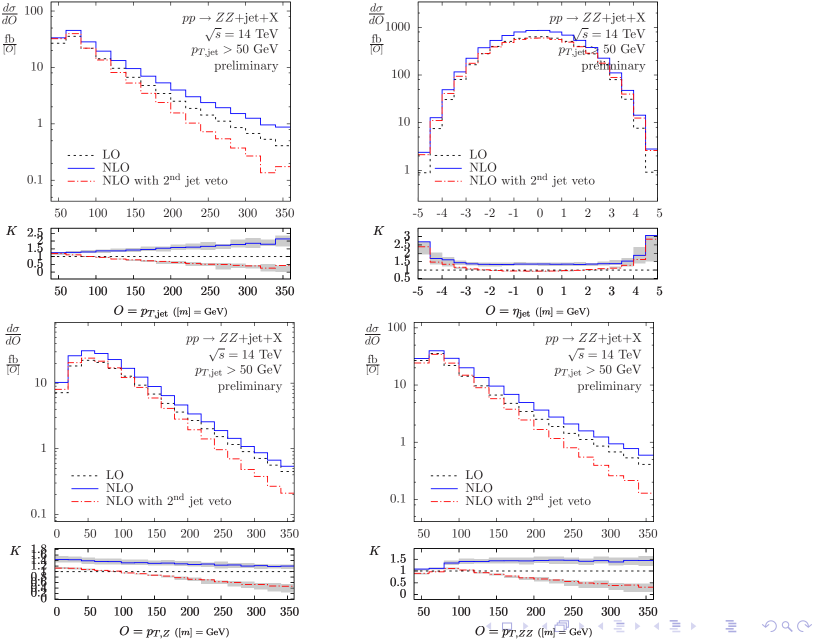
Differential distributions: Tevatron



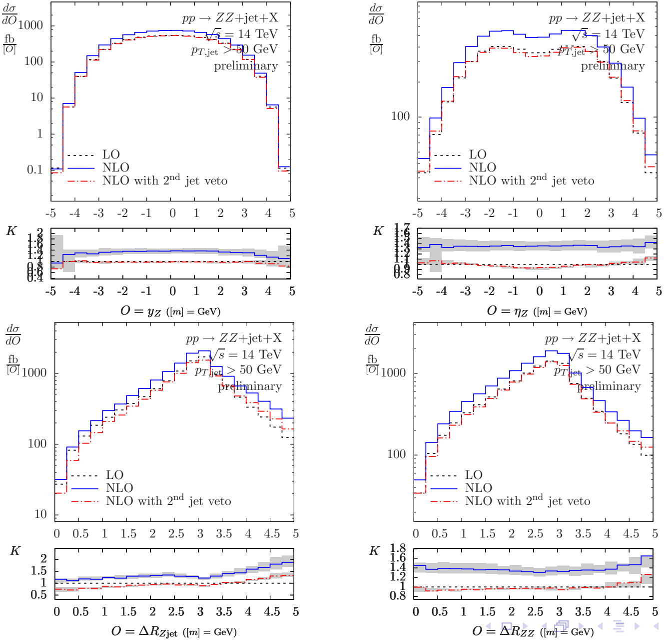
Differential distributions: Tevatron



Differential distributions: LHC



Differential distributions: LHC

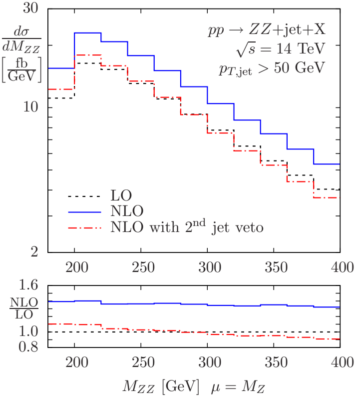


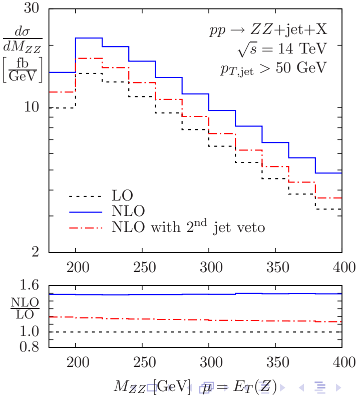
Fixed and dynamic scale choices: LHC

$$\mu = E_T(Z) = \sum E_{T,Z};\quad \mu = H_T = \sum E_{T,Z} + \sum E_{T,\text{parton}};\quad \mu = M_{ZZ}$$

with $\mu := \mu_R = \mu_F$, and $E_T = (p_T^2 + m^2)^{1/2}$

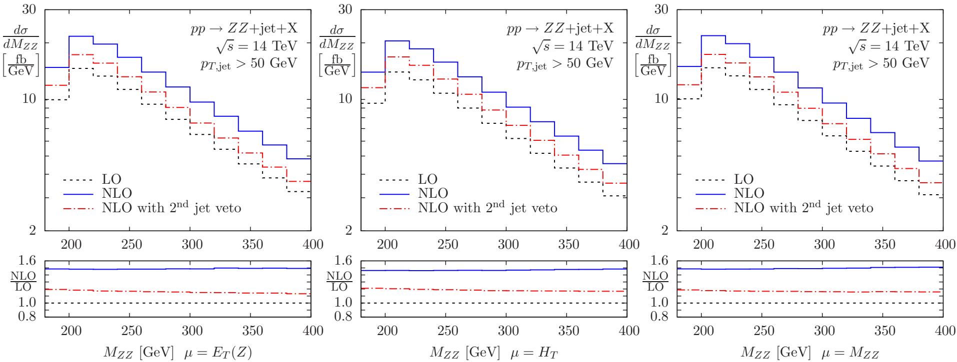
μ	σ_{LO} [pb]	$\sigma_{\text{NLO,incl}}$ [pb]	$\sigma_{\text{NLO,excl}}$ [pb]	K_{incl}	K_{excl}
M_Z	2.7	3.7	2.6	1.4	1.0
$E_T(Z)$	2.3	3.4	2.6	1.5	1.2
H_T	2.1	3.2	2.5	1.5	1.2
M_{ZZ}	2.2	3.3	2.6	1.5	1.2





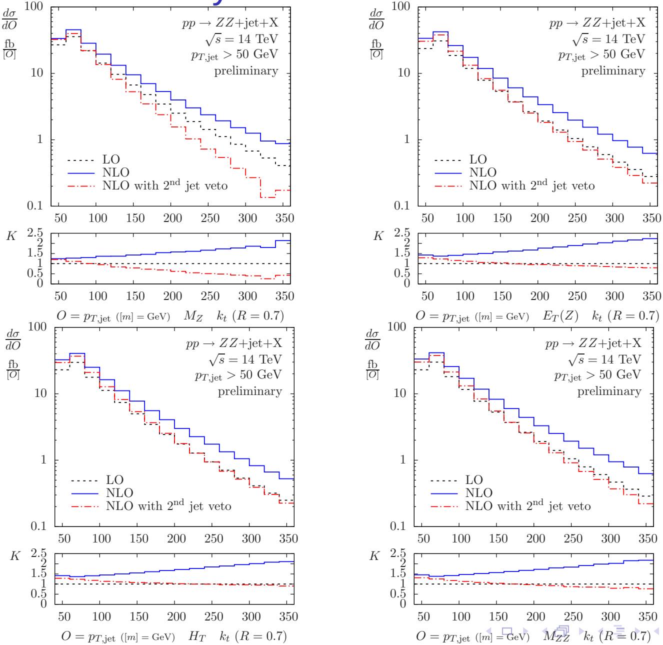
Fixed and dynamic scale choices: LHC

Dynamic scales comparison

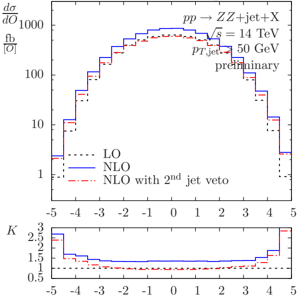


in progress: jet algorithm comparison (k_t Ellis, Soper and SISCone Salam, Soyez with $R = 0.7, 0.4$)

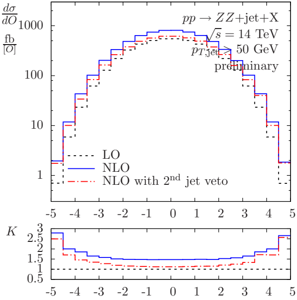
Fixed and dynamic scale choices: LHC



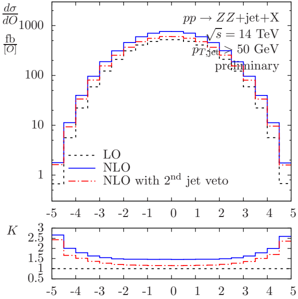
Fixed and dynamic scale choices: LHC



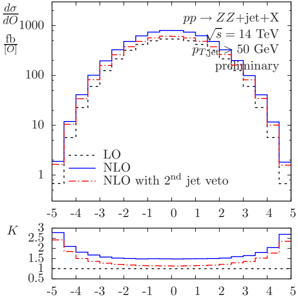
$O = \eta_{\text{jet}}$ ($[m] =$ GeV) M_Z k_t $(R = 0.7)$



$O = \eta_{\text{jet}}$ ($[m] =$ GeV) $E_T(Z)$ k_t $(R = 0.7)$



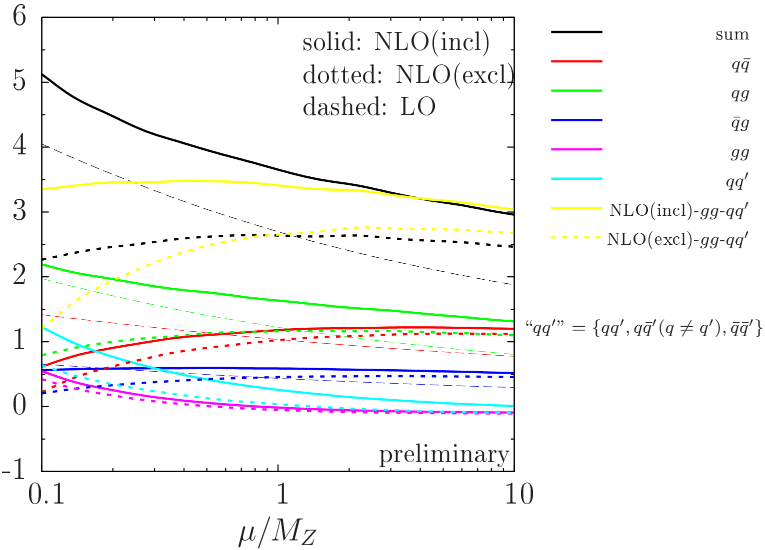
$O = \eta_{\text{jet}}$ ($[m] =$ GeV) H_T k_t $(R = 0.7)$



$O = \eta_{\text{jet}}$ ($[m] =$ GeV) M_{ZZ} k_t $(R = 0.7)$

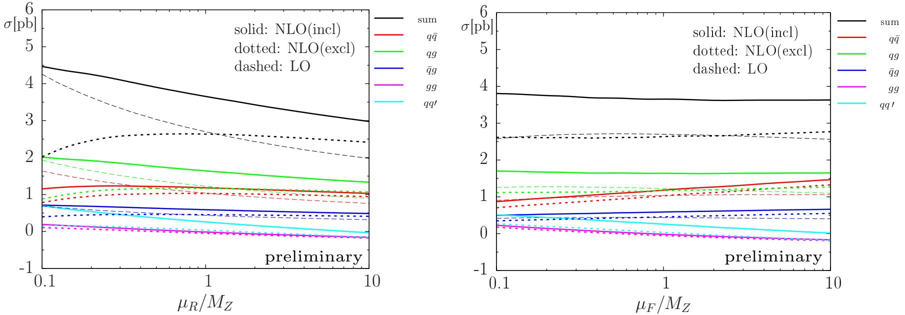
LHC scale variation: subprocess dependence

same-direction variation ($\mu := \mu_R = \mu_F$)



LHC scale variation: subprocess dependence

independent variation of μ_R and μ_F



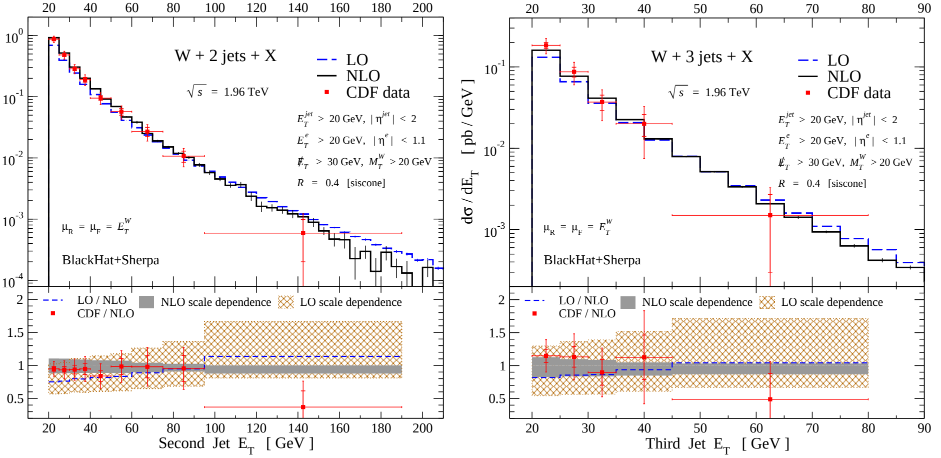
left: $\mu_R/M_Z \in [0.1, 10]$, $\mu_F = M_Z$; right: $\mu_F/M_Z \in [0.1, 10]$, $\mu_R = M_Z$

NLO QCD calculation for W + n jets $(n \leq 4)$

BlackHat+Sherpa group:

C.F. Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

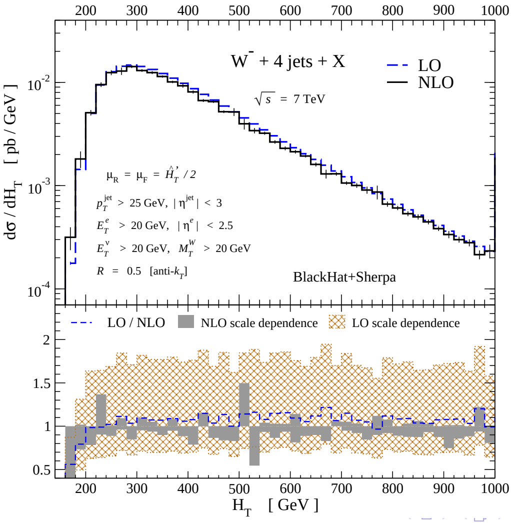
W + 2 jets and W + 3 jets at the Tevatron:



NLO QCD calculation for W + n jets $(n \leq 4)$

BlackHat+Sherpa group

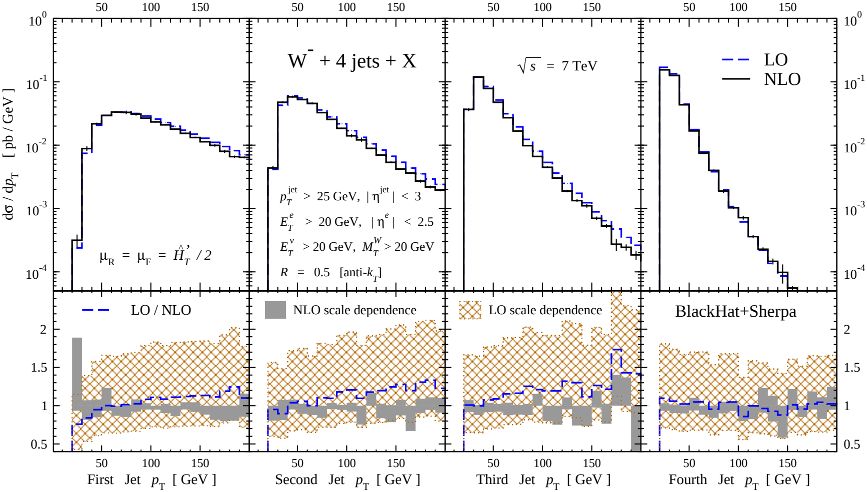
W^- + 4 jets at LHC (7 TeV): $H_T = \sum_{\text{jets}\,j} E_T^j + E_T^e + E_T^\nu$ distribution



NLO QCD calculation for W + n jets $(n \leq 4)$

BlackHat+Sherpa group

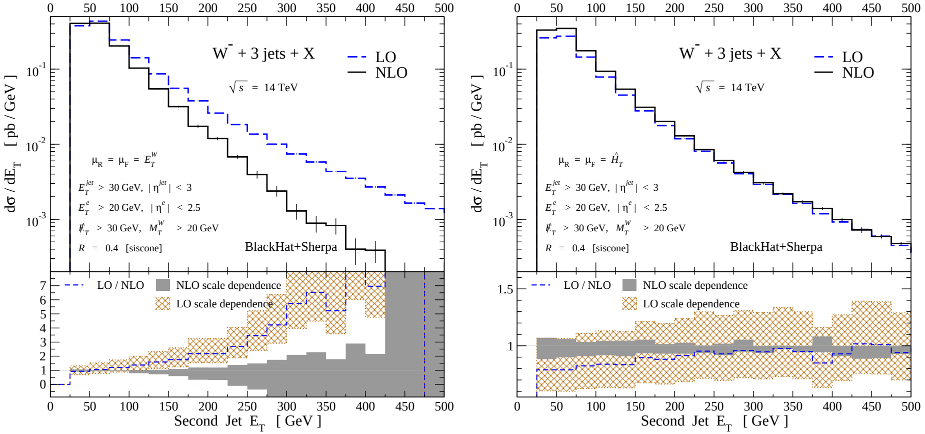
W^- + 4 jets at the LHC (7 TeV):



Scale choices in V + jets

BlackHat+Sherpa group

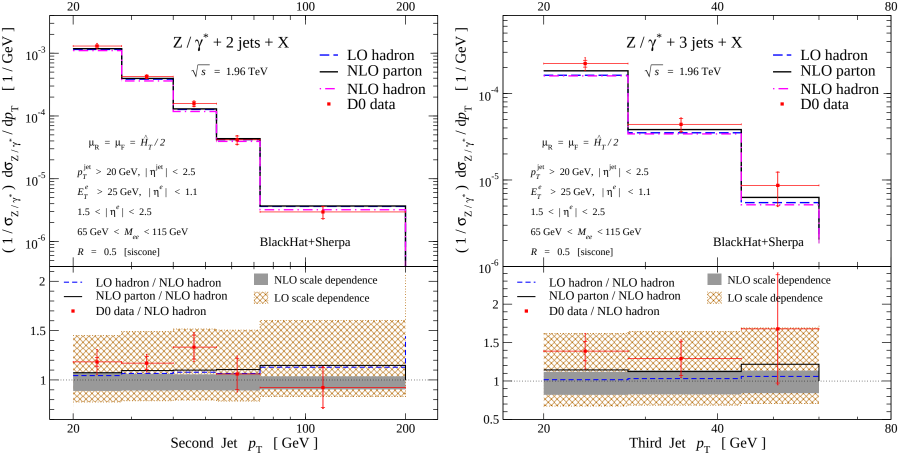
W^- + 3 jets at the LHC (14 TeV):



NLO QCD calculation for $Z + n$ jets $(n \leq 3)$

BlackHat+Sherpa group

$Z + 2$ jets and $Z + 3$ jets at the Tevatron:



Data-driven estimation methods

Normalising weak boson pair production at the LHC

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

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

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

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

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

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

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

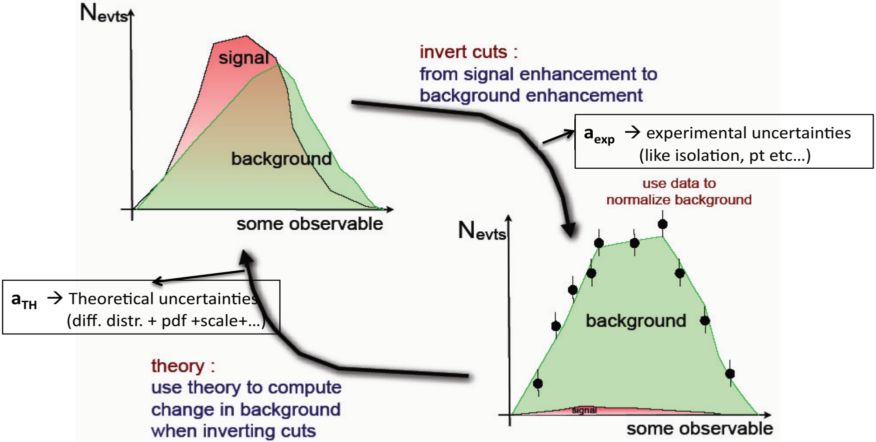
Scale uncertainty reduction for $(ZZ \to 4\ell)$/DY

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

The control of the background



invert cuts :
from signal enhancement to
background enhancement

a_{exp} → experimental uncertainties
(like isolation, pt etc...)

use data to
normalize background

a_{TH} → Theoretical uncertainties
(diff. distr. + pdf +scale+...)

theory :
use theory to compute
change in background
when inverting cuts

$$\boxed{N^{B}_{(\text{signal region})} = a_{exp} * a_{TH} * N^{B}_{\text{control region}}}$$

a_{exp} - uncorr between exp
a_{TH} - 100% correlated [1]

Conclusions

- Experimental TeV scale physics exploration has started
- Need solid theoretical predictions for signals and backgrounds
- Weak boson + jets production:
  important backgrounds
  $\longrightarrow$ higher order corrections required
  and becoming available
  even for high jet multiplicities
- Combining theory predictions and LHC data allows to improve predictions as well as validation/cross checks