

Z -boson pair + 1-jet production at NLO QCD

Nikolas Kauer

Royal Holloway, University of London

in collaboration with

Jennifer Archibald, Thomas Binoth, Tanju Gleisberg, Stefan Karg, Grégory Sanguinetti

HP² High Precision for Hard Processes at the LHC Workshop

Galileo Galilei Institute for Theoretical Physics, Florence, Italy

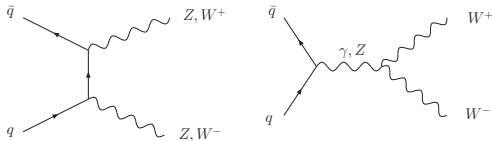
September 14, 2010



Outline

- Weak boson pair (+ jets) production
- Weak bosons: importance for LHC physics
- NLO QCD calculation for $ZZ + \text{jet}$
- Computational details
- Tuned comparison with DKU's calculation
- Results
- Summary

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

- $pp, p\bar{p} \rightarrow ZZ, WW + \text{jet}$ 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 $pp \rightarrow WW + 2 \text{ jets}, ZZ + 2 \text{ jets}, WZ + 2 \text{ jets}$ at NLO QCD with leptonic decays
B. Jäger, Oleari, Zeppenfeld (2006); Bozzi, B. Jäger, Oleari, Zeppenfeld (2007)

comprehensive list of references $\rightarrow$ e.g. arXiv:0911.3181 [hep-ph]

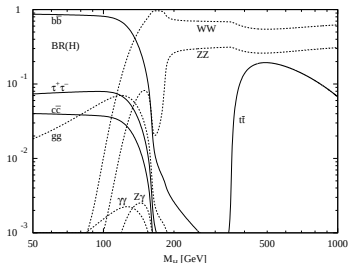
Weak bosons: importance for LHC physics

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

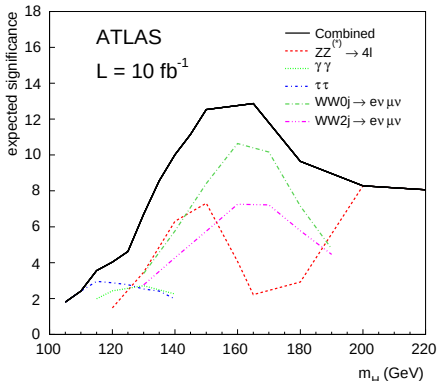
- ▶ dark matter candidate → **signatures** with $\cancel{E}_T$
- ▶ cascade decays with new EW gauge bosons/gauginos → $\ell^\mp$
- ▶ cascade decays of new coloured particles → **jets**

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

LHC search for SM & BSM Higgs



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



Updated experimenter's wishlist for LHC processes

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

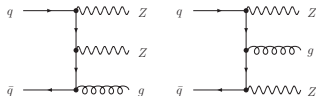
NLO QCD calculation for $ZZ + \text{jet}$

H/NP background, $ZZ + \text{jet}$ @ NLO: component of ZZ @ NNLO, anomalous couplings searches

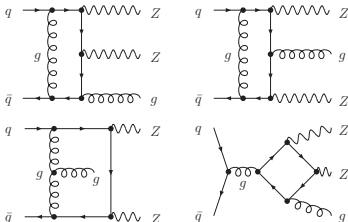
(no $ZZ\gamma$ or ZZZ coupling in SM)

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

LO amplitude contributions



Virtual corrections contributions



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

Computational 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 $\rightarrow$ 3 status: complete and cross checked

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 $\rightarrow$ 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 $1, 2 \rightarrow 3, 4, 5$:

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

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 $N_f = 5$, and we use the default LHAPDF values leading to $\alpha_s^{\text{LO}}(91.188 \text{ GeV}) = 0.129783$ and $\alpha_s^{\text{NLO}}(91.70 \text{ GeV}) = 0.1179$. 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 $m_t = 174.3 \text{ GeV}$, the masses of all other quarks are neglected. The weak boson masses are $M_Z = 91.188 \text{ GeV}$ and $M_H = 150 \text{ GeV}$. 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 $p_{T,\text{jet}} > 50 \text{ GeV}$.

Comparison for single phase space point

	$ \mathcal{M}_{\text{LO}} ^2 / e^4 / g_s^2 [\text{GeV}^{-2}]$
$u\bar{u} \rightarrow ZZg$	(12-13 digit agreement)
BGKKS	9.081603376311467 · 10 ⁻⁴
DKU	9.081603376315696 · 10 ⁻⁴
$d\bar{d} \rightarrow ZZg$	
BGKKS	1.892589730735170 · 10 ⁻³
DKU	1.892589730736050 · 10 ⁻³
$ug \rightarrow ZZg$	
BGKKS	1.687614989680196 · 10 ⁻⁴
DKU	1.687614989680182 · 10 ⁻⁴
$dg \rightarrow ZZg$	
BGKKS	3.516959138773490 · 10 ⁻⁴
DKU	3.516959138773458 · 10 ⁻⁴
$g\bar{u} \rightarrow ZZg$	
BGKKS	1.319241114194492 · 10 ⁻⁵
DKU	1.319241114194495 · 10 ⁻⁵
$g\bar{d} \rightarrow ZZg$	
BGKKS	2.749274639763224 · 10 ⁻⁵
DKU	2.749274639763229 · 10 ⁻⁵

Virtual corrections for single PS point

	$c_0^{\text{bos}} [\text{GeV}^{-2}]$	$c_0^{\text{ferm}} [\text{GeV}^{-2}]$
<u>$u\bar{u} \rightarrow ZZg$</u>		(8-12 digit agreement)
BGKKS	2.571718370986939 · 10 ⁻⁴	2.771274006707126 · 10 ⁻⁶
DKU	2.571718370988091 · 10 ⁻⁴	2.771273991103833 · 10 ⁻⁶
<u>$d\bar{d} \rightarrow ZZg$</u>		
BGKKS	5.335637852921577 · 10 ⁻³	3.553804947755081 · 10 ⁻⁶
DKU	5.335637852923933 · 10 ⁻³	3.553804924505993 · 10 ⁻⁶
<u>$ug \rightarrow ZZg$</u>		
BGKKS	3.455303690923093 · 10 ⁻⁴	-1.575277709579237 · 10 ⁻⁶
DKU	3.455303690940059 · 10 ⁻⁴	-1.575277712403393 · 10 ⁻⁶
<u>$dg \rightarrow ZZg$</u>		
BGKKS	7.182218731401221 · 10 ⁻⁴	-2.134836868278616 · 10 ⁻⁶
DKU	7.182218731436469 · 10 ⁻⁴	-2.134836871947412 · 10 ⁻⁶
<u>$g\bar{u} \rightarrow ZZg$</u>		
BGKKS	7.284079447744509 · 10 ⁻⁵	-3.877856878313408 · 10 ⁻⁶
DKU	7.284079439746620 · 10 ⁻⁵	-3.877856878314387 · 10 ⁻⁶
<u>$g\bar{d} \rightarrow ZZg$</u>		
BGKKS	1.505448756089957 · 10 ⁻⁵	-4.839140375435081 · 10 ⁻⁶
DKU	1.505448754415003 · 10 ⁻⁵	-4.839140375436319 · 10 ⁻⁶

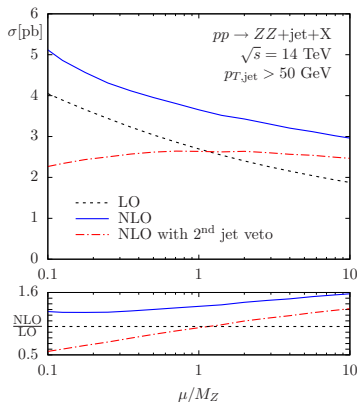
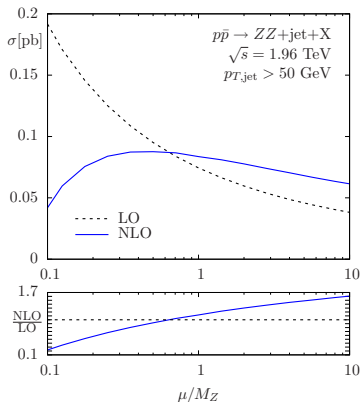
Integrated cross section comparison

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

good agreement within uncertainties

(MC-integration error dominates)

Results: ZZ + jet production at LO and NLO



Input parameters/settings:

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

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

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

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

LHC

$\Delta\sigma/\sigma(pp \rightarrow ZZ + \text{jet}), \sqrt{s} = 14 \text{ TeV}$			
	$\mu/M_Z \in [\frac{1}{2}, 2]$	$\mu/M_Z \in [\frac{1}{4}, 4]$	$\mu/M_Z \in [\frac{1}{8}, 8]$
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

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

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

Tevatron

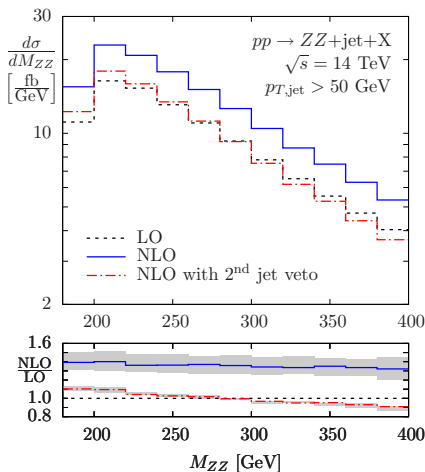
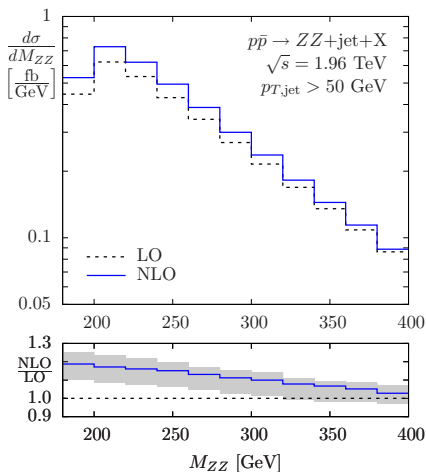
	$\sigma(p\bar{p} \rightarrow ZZ + \text{jet})$ [pb], $\sqrt{s} = 1.96$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	0.27202(3)	0.07456(1) ^{+28%} _{-20%}	0.016037(2)	0.0012651(1)
NLO	0.3307(6)	0.0836(1) ^{+5%} _{-7%}	0.01583(4)	0.000976(4)

LHC

	$\sigma(pp \rightarrow ZZ + \text{jet})$ [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)

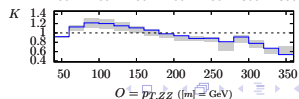
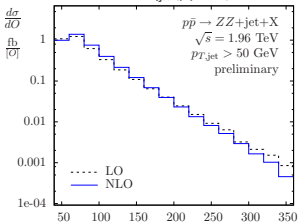
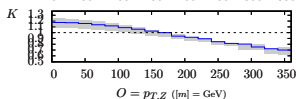
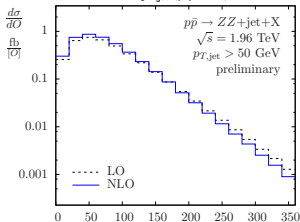
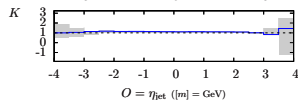
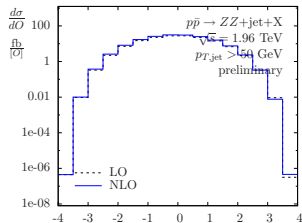
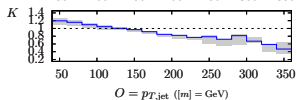
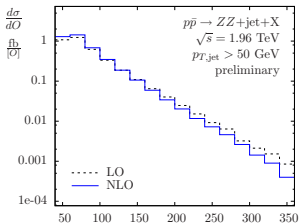
A sample differential distribution

ZZ invariant mass distribution at the Tevatron and LHC

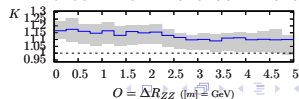
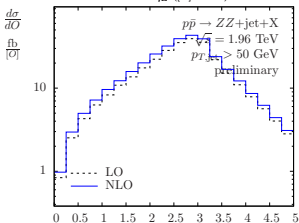
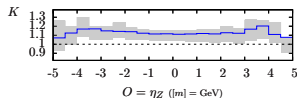
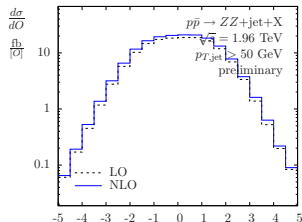
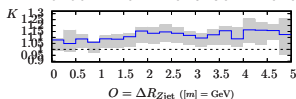
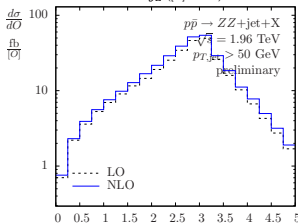
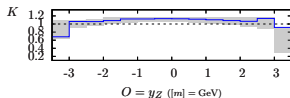
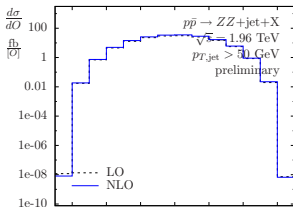


K -factor band: $[d\sigma_{\text{NLO}}/dM_{ZZ}](\mu)/[d\sigma_{\text{LO}}/dM_{ZZ}](M_Z)$ with $\mu/M_Z \in [\frac{1}{2}, 2]$

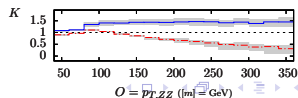
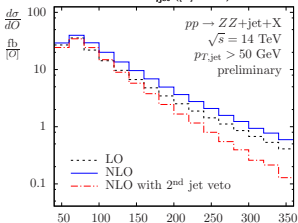
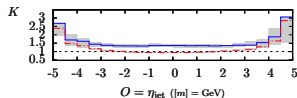
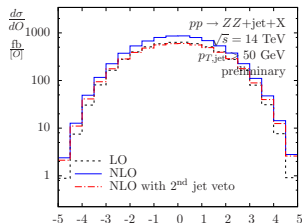
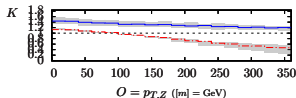
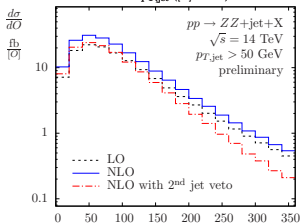
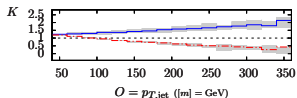
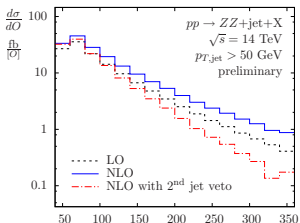
Differential distributions: Tevatron



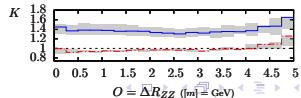
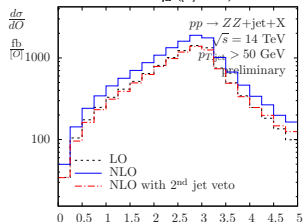
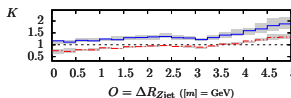
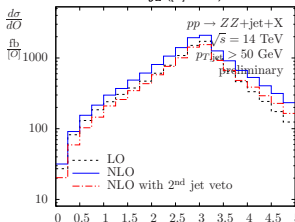
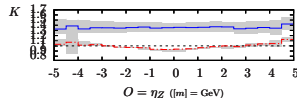
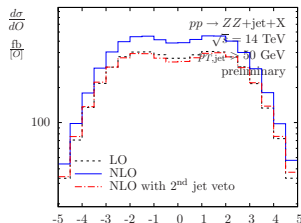
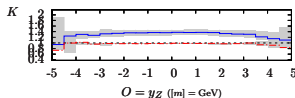
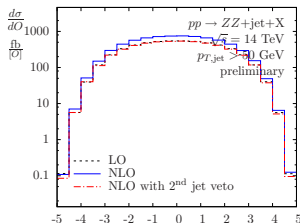
Differential distributions: Tevatron



Differential distributions: LHC



Differential distributions: LHC

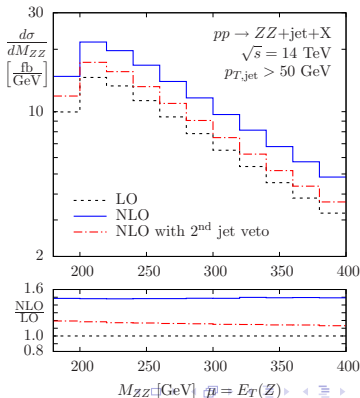
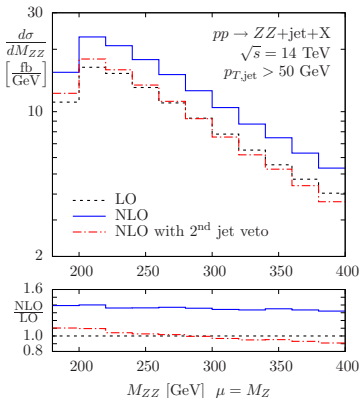


Fixed and dynamic scale choices: LHC

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

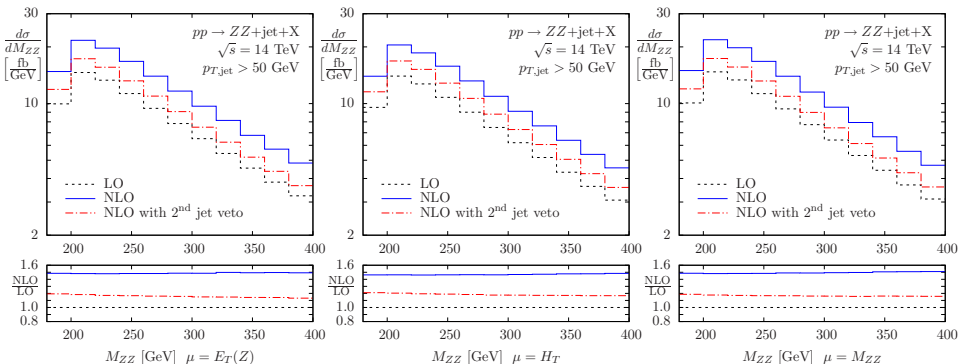
$$\text{with } \mu := \mu_R = \mu_F, \text{ and } E_T = (p_T^2 + m^2)^{1/2}$$

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



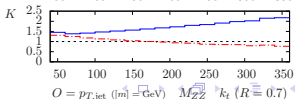
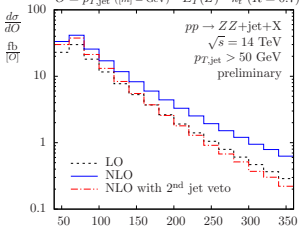
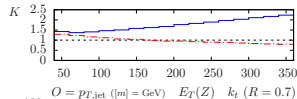
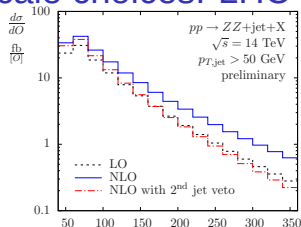
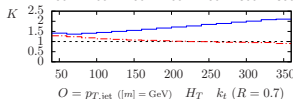
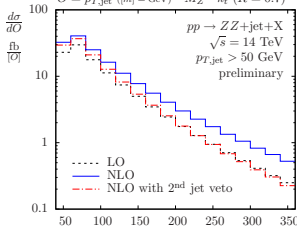
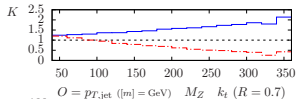
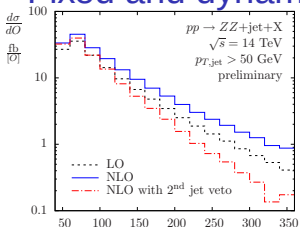
Fixed and dynamic scale choices: LHC

Dynamic scales comparison

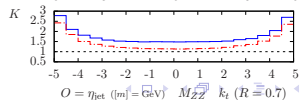
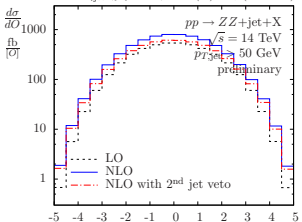
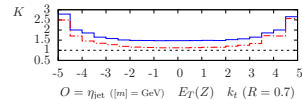
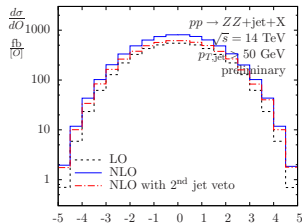
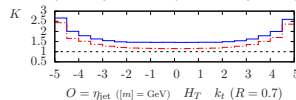
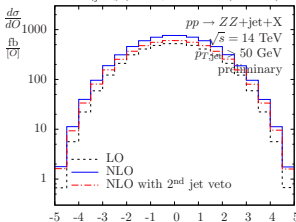
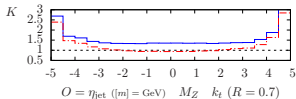
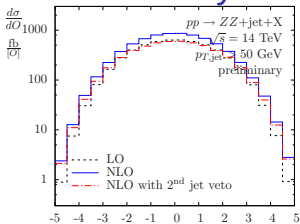


in progress: jet algorithm comparison (k_t Ellis, Soper and SIScone Salam, Soyez with $R = 0.7, 0.4$)

Fixed and dynamic scale choices: LHC

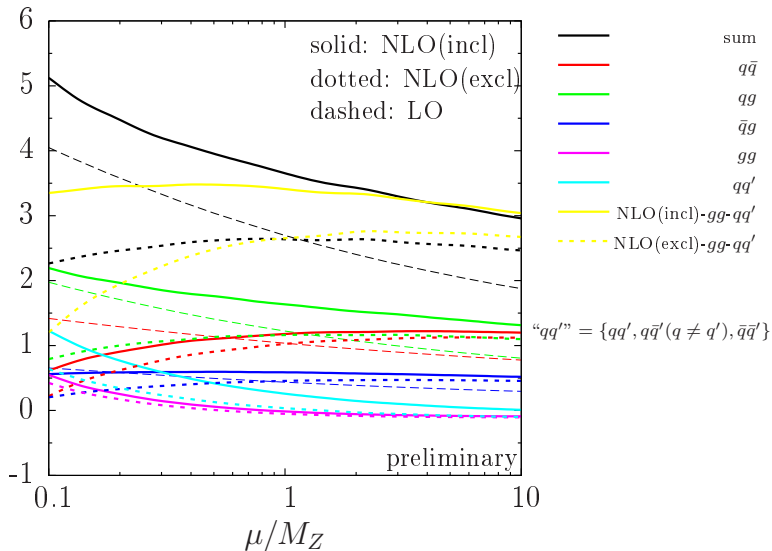


Fixed and dynamic scale choices: LHC



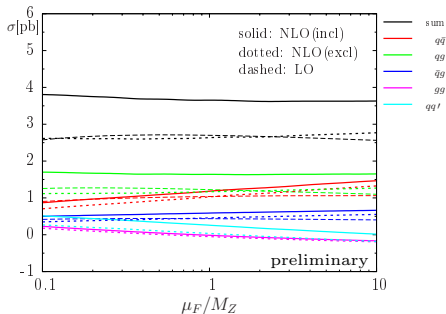
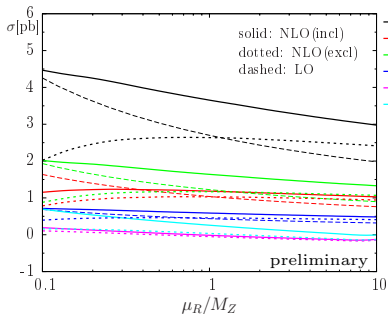
LHC scale variation: subprocess dependence

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

Summary

- ▶ $pp \rightarrow ZZ + \text{jet}$ @ NLO needed to predict ZZ (+ jet) LHC backgrounds and control theoretical uncertainty
- ▶ $pp \rightarrow ZZ + \text{jet}$ @ NLO is component of $pp \rightarrow ZZ$ @ NNLO
- ▶ NLO $ZZ + \text{jet}$ calculation using Golem/Catani-Seymour methods and Golem/Sherpa implementation
- ▶ successful detailed comparison with DKU's calculation
- ▶ essential: differential description of K factor and scale uncertainty
- ▶ selection cuts (e.g. jet veto) can strongly affect K factor and uncertainty
- ▶ selection cuts can reduce LO-type contributions at NLO and hence improve the NLO uncertainty