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

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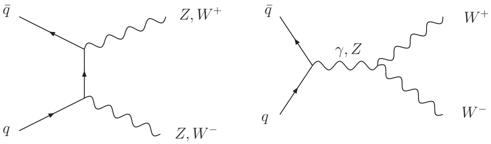
Outline

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

Predictions for weak boson pair production



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

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

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

- $gg \to ZZ, WW$ (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 $q\bar{q} \to WW$ ⟶ NNLO QCD correction

Chachamis, Czakon, Eiras (2008)

Predictions for weak boson pair + jets production

- $pp, p\bar{p} \to ZZ, WW$ + 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 $pp \to WW$ + 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)

comprehensive list of references ⟶ e.g. arXiv:0911.3181 [hep-ph]

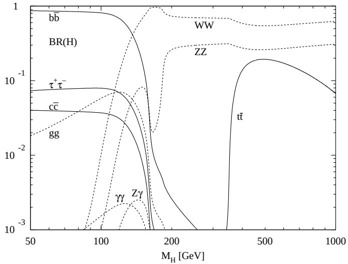
Weak bosons: importance for LHC physics

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

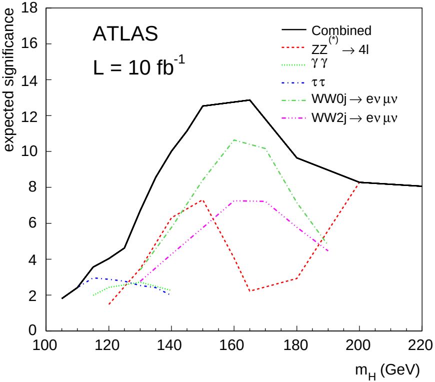
- dark matter candidate ⟶ signatures with $\not{E}_T$
- cascade decays with new EW gauge bosons/gauginos ⟶ $\ell^\mp$
- cascade decays of new coloured particles ⟶ jets

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

LHC search for SM & BSM Higgs



$H \rightarrow VV$ 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. $pp \to VV$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

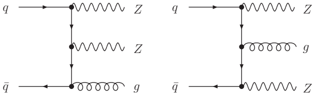
NLO QCD calculation for ZZ + jet

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

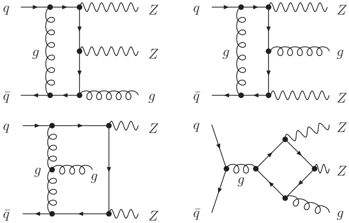
(no $ZZ\gamma$ or ZZZ coupling in SM)

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

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

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 $N_\mathrm{f} = 5$, 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

	$\lvert\mathcal{M}_{\mathrm{LO}}\rvert^2/e^4/g_{\mathrm{s}}^2[\mathrm{GeV}^{-2}]$
$u\bar{u} \to ZZg$	**(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

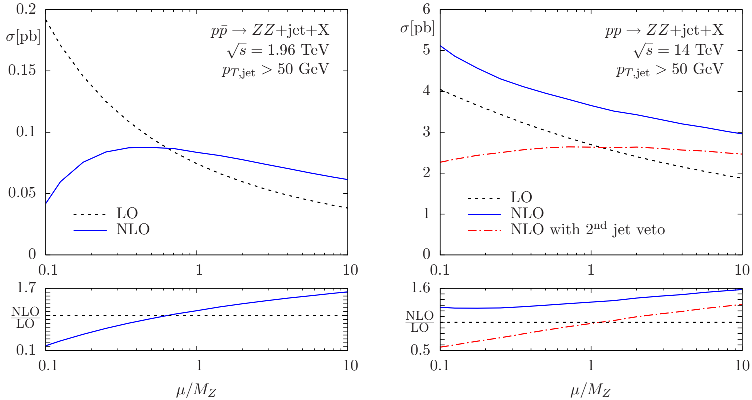
	$c_0^{\text{bos}}[\text{GeV}^{-2}]$	$c_0^{\text{ferm}}[\text{GeV}^{-2}]$
$u\bar{u} \to ZZg$		**(8-12 digit agreement)**
BGKKS	$2.571718370986939 \cdot 10^{-4}$	$2.771274006707126 \cdot 10^{-6}$
DKU	$2.571718370988091 \cdot 10^{-4}$	$2.771273991103833 \cdot 10^{-6}$
$d\bar{d} \to ZZg$		
BGKKS	$5.335637852921577 \cdot 10^{-3}$	$3.553804947755081 \cdot 10^{-6}$
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

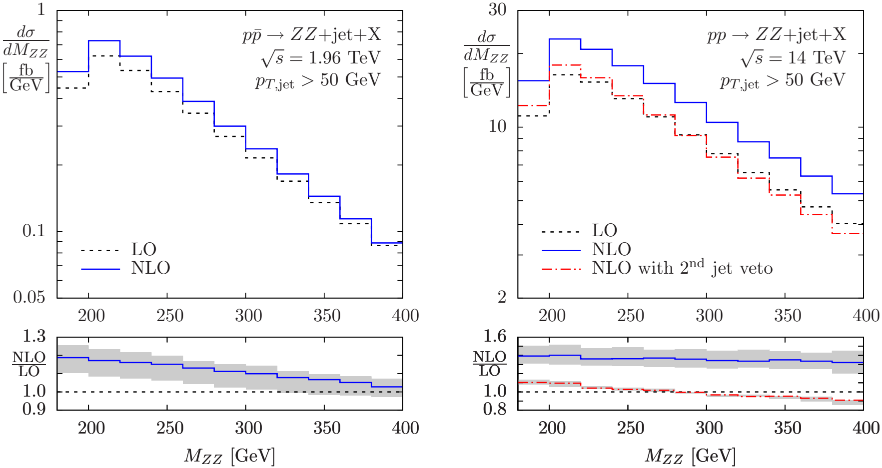
	$\sigma(p\bar{p} \to ZZ + \text{jet})$ [pb], $\sqrt{s} = 1.96$ TeV			
$p_{T,\text{jet}}$ cut [GeV]	20	50	100	200
LO	$0.27202(3)$	$0.07456(1)^{+28\%}_{-20\%}$	$0.016037(2)$	$0.0012651(1)$
NLO	$0.3307(6)$	$0.0836(1)^{+5\%}_{-7\%}$	$0.01583(4)$	$0.000976(4)$

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		$2.637(9)^{+0.2\%}_{-1\%}$	$0.755(4)$	$0.1005(9)$

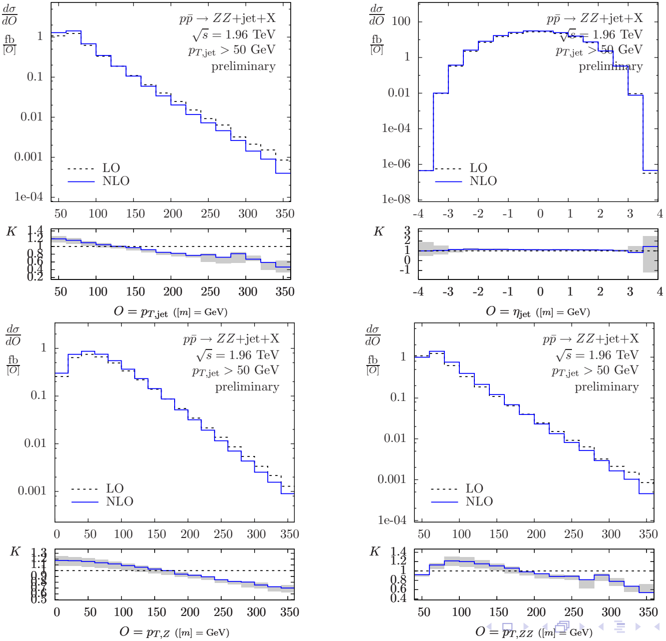
A sample differential distribution

ZZ invariant mass distribution at the Tevatron and LHC

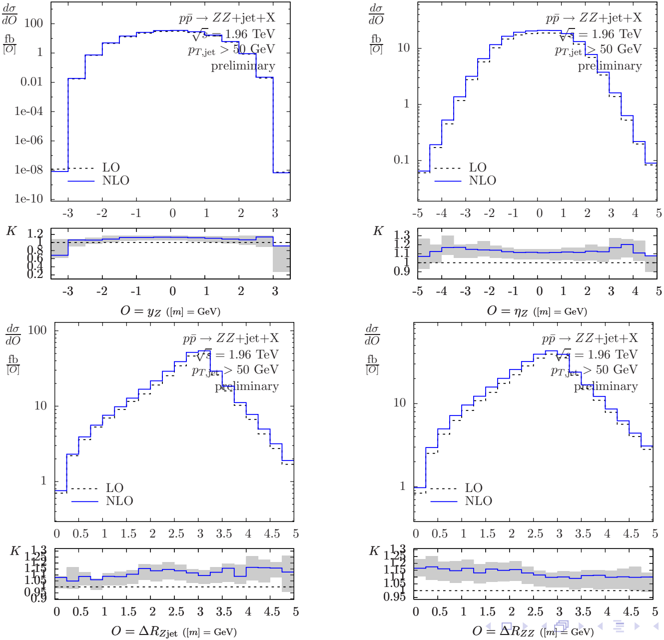


K-factor band: $[d\sigma_{\text{NLO}}/dM_{ZZ}](\mu)/[d\sigma_{\text{LO}}/dM_{ZZ}](M_Z)$ with $\mu/M_Z \in [\frac{1}{2}, 2]$

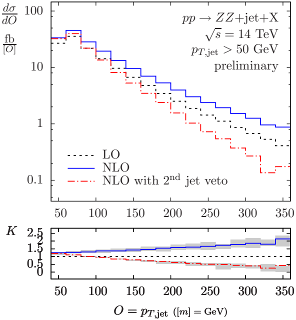
Differential distributions: Tevatron

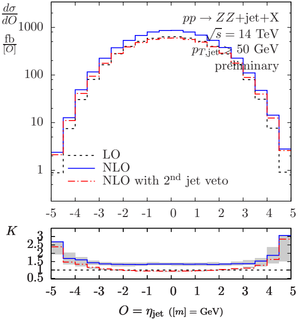


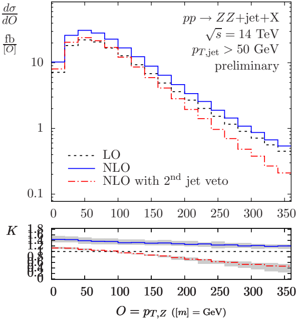
Differential distributions: Tevatron

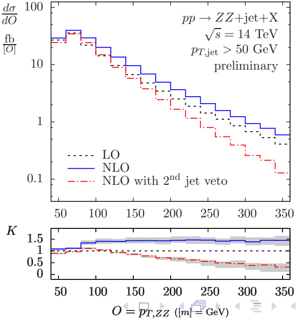


Differential distributions: LHC

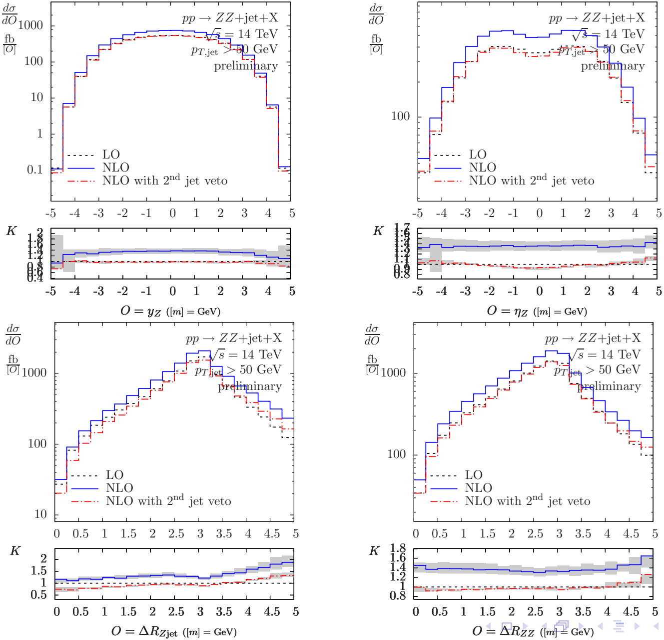








Differential distributions: LHC

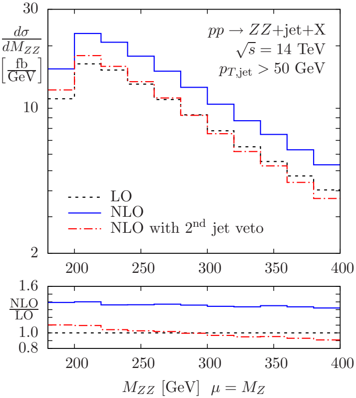


Fixed and dynamic scale choices: LHC

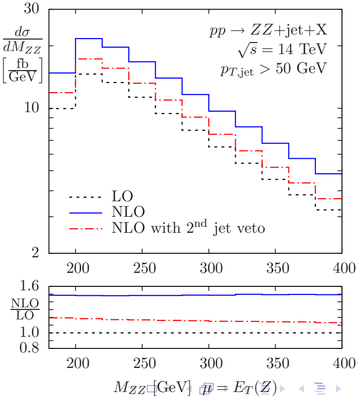
$$\mu = E_T(Z) = \sum E_{T,Z};\ \ \mu = H_T = \sum E_{T,Z} + \sum E_{T,\text{parton}};\ \ \mu = M_{ZZ}$$

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



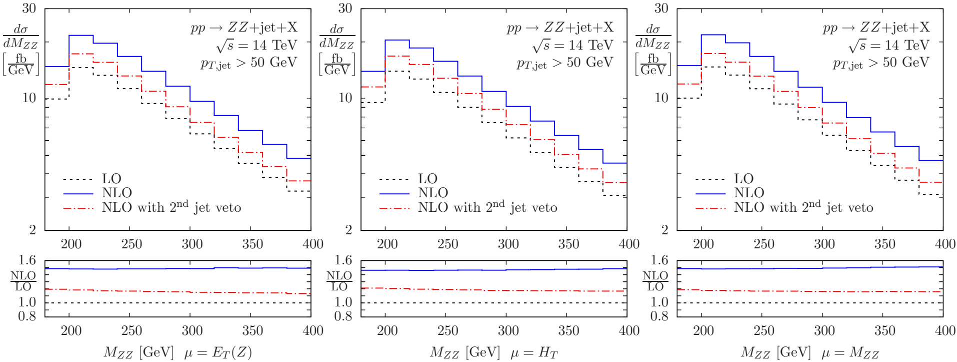
$\mu = M_Z$



$\mu = E_T(Z)$

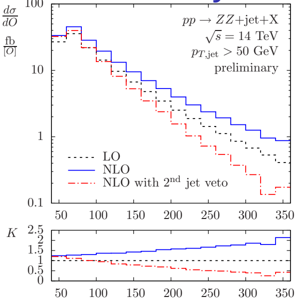
Fixed and dynamic scale choices: LHC

Dynamic scales comparison

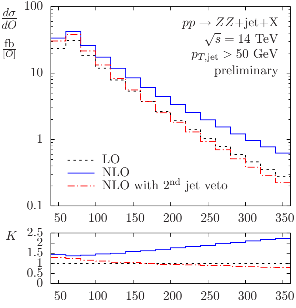


in progress: jet algorithm comparison (k_t Ellis, Soper and SISCone Salam, Soyez with $R = 0.7, 0.4$)

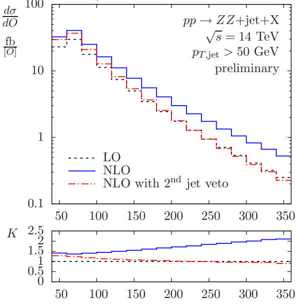
Fixed and dynamic scale choices: LHC



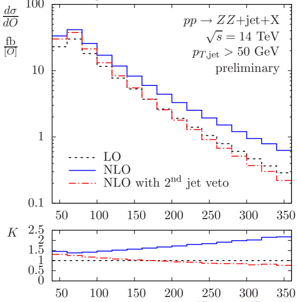
$O = p_{T,\text{jet}}$ ([m] = GeV) M_Z k_t ($R = 0.7$)



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

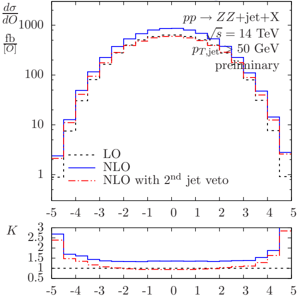


$O = p_{T,\text{jet}}$ ([m] = GeV) H_T k_t ($R = 0.7$)

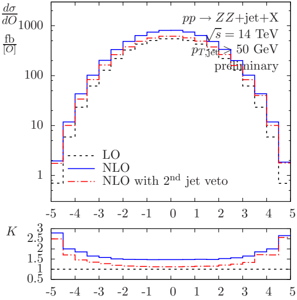


$O = p_{T,\text{jet}}$ ([m] = GeV) M_{ZZ} k_t ($R = 0.7$)

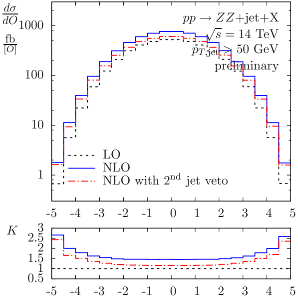
Fixed and dynamic scale choices: LHC



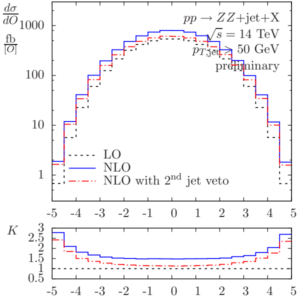
$O = \eta_{\text{jet}}$ ($[m] = \text{GeV}$) M_Z k_t ($R = 0.7$)



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



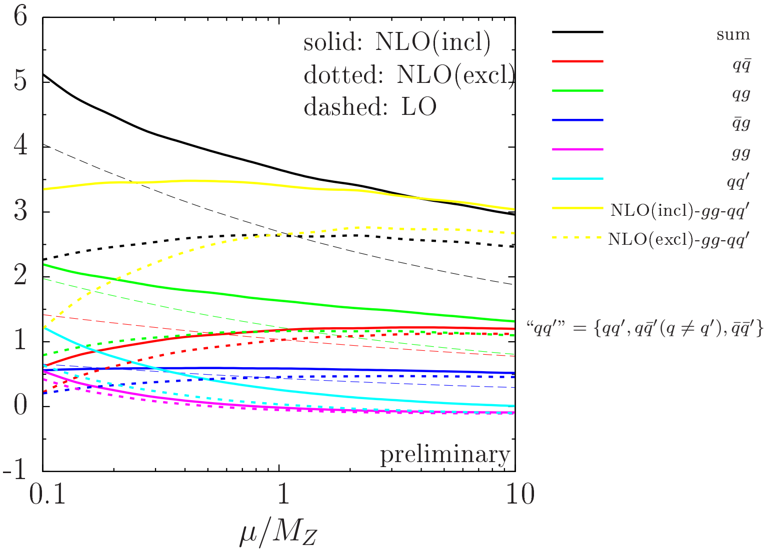
$O = \eta_{\text{jet}}$ ($[m] = \text{GeV}$) H_T k_t ($R = 0.7$)



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

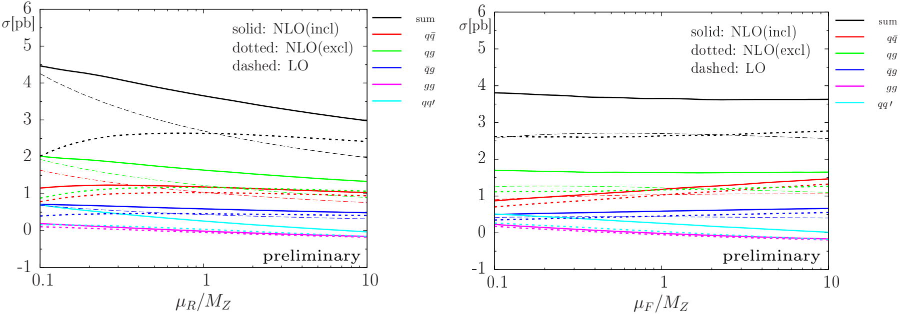
LHC scale variation: subprocess dependence

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

Summary

- $pp \to ZZ$ + jet @ NLO needed to predict ZZ (+ jet) LHC backgrounds and control theoretical uncertainty
- $pp \to ZZ$ + jet @ NLO is component of $pp \to ZZ$ @ NNLO
- NLO ZZ + 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