VV Production at High Transverse Momenta and Anomalous Couplings

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Institute of Theoretical Physics, Karlsruhe Instittute of Technology

Contents

- Introduction
- Differential distributions at approximate NNLO
- Anomalous coupling effects in WZ
- Summary

Introduction

Goal

Test Standard Model & Hints of New Physics

Method

Improve SM prediction — Reduce Theory Uncertainty

Framework to parametrize Beyond Standard Model physics → Effective Field Theory ⇓ Anomalous Couplings

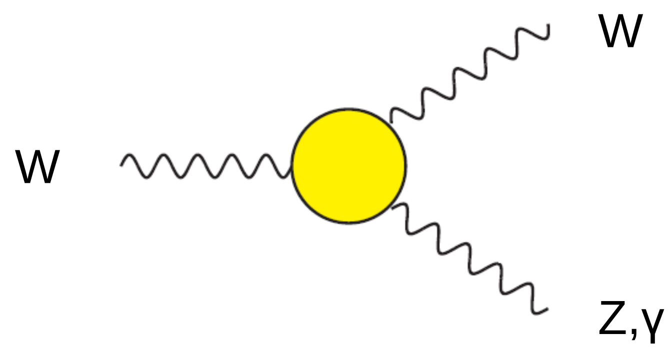
Improve Sensitivity — Cuts and Observables

Tools

VBFNLO: Diboson (+ up to 2 jet) production at NLO with AC
LoopSim: Merge NLO samples to provide approximate higher order

Di-boson production

- Background to many SM and BSM searches (including Higgs)
- Search for New Physics through Anomalous couplings



Status:

- NLO QCD known for a long time: 40-300%
- NLO EW known for almost all processes(on-shell): in tails up to 30%
- LO QCD GF induced contribution (NNLO) known: up to 20%
- Full NNLO QCD known for almost all processes: on-shell: γγ,WW
  decays: Zγ,Wγ,ZZ

AC via Effective Theory

- New Physics at high mass scale: Λ
- Higher-dimension terms to Lagrangian: 1/ Λ

➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_k}{\Lambda^4}\cdots$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi)$$

Effective Theory

- New Physics at a high mass scale: Λ
- Higher-dimension terms to Lagrangian 1/ Λ^n

➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings

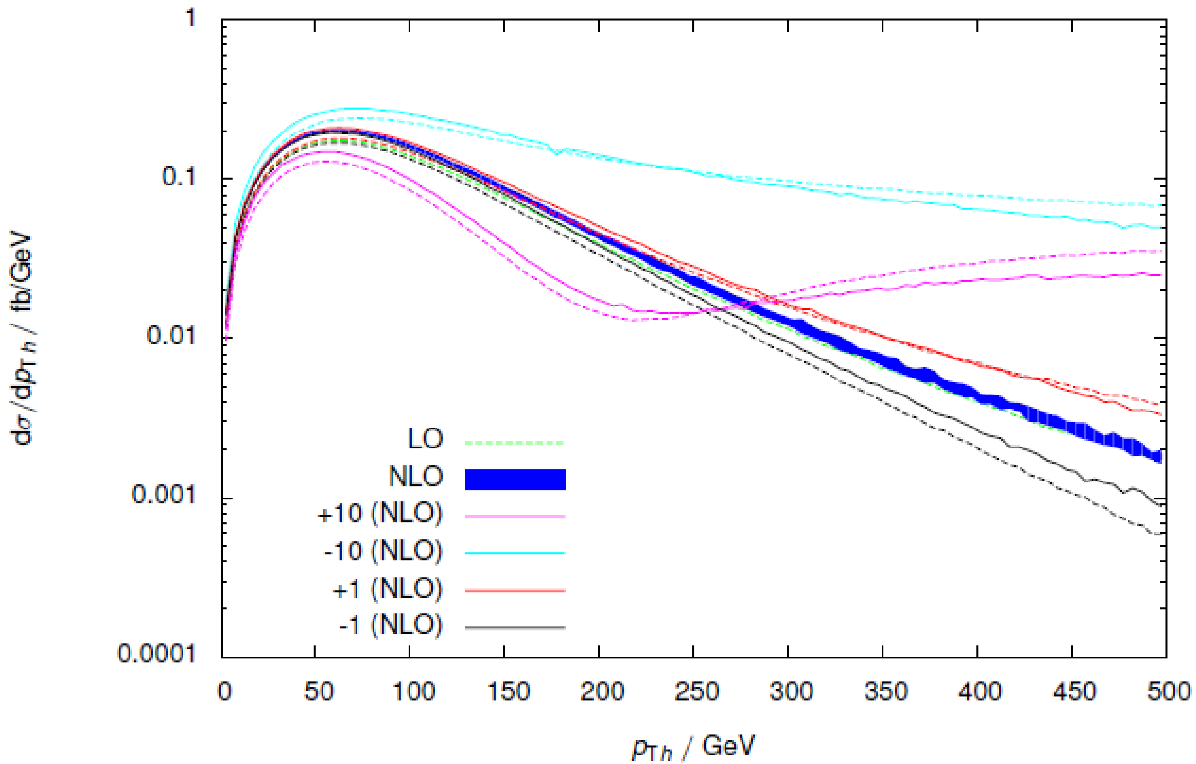
WWH Vertex:

$$\underbrace{igm_W g^{\mu\nu}}_{\text{SM}} \underbrace{-\frac{1}{2} i \frac{f_W}{\Lambda^2} g m_W \left(-g^{\mu\nu} \left(p_h \cdot p_- + p_h \cdot p_+ \right) + p_h^\nu p_-^\mu + p_h^\mu p_+^\nu \right)}_{\mathcal{O}_W}$$

Effective Theory

- New Physics at a high mass scale: Λ
- Higher-dimension terms to Lagrangian 1/ Λ^n

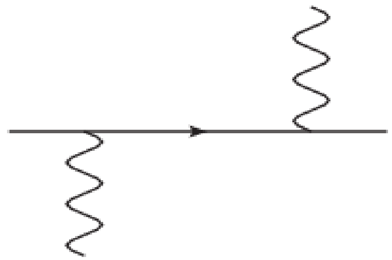
➡ Parametrize deviations from SM, e.g. in triple/quartic gauge couplings



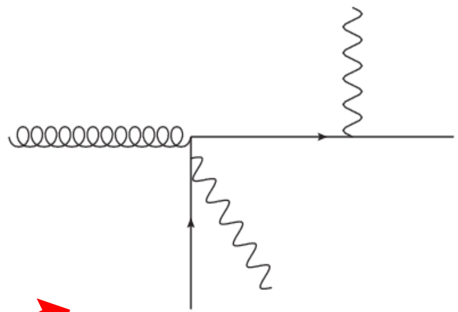
Beyond NLO QCD

- NLO QCD corrections large
  - New sub-processes
  - New topologies
- At NNLO
  - New sub-processes
  - New topologies
- Potentially large corrections

LO

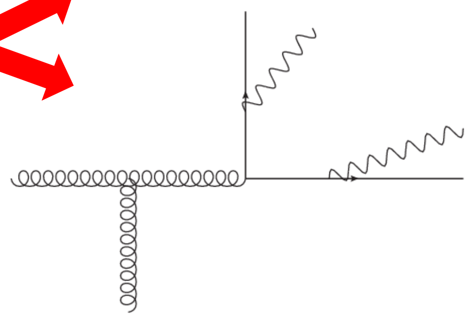


NLO



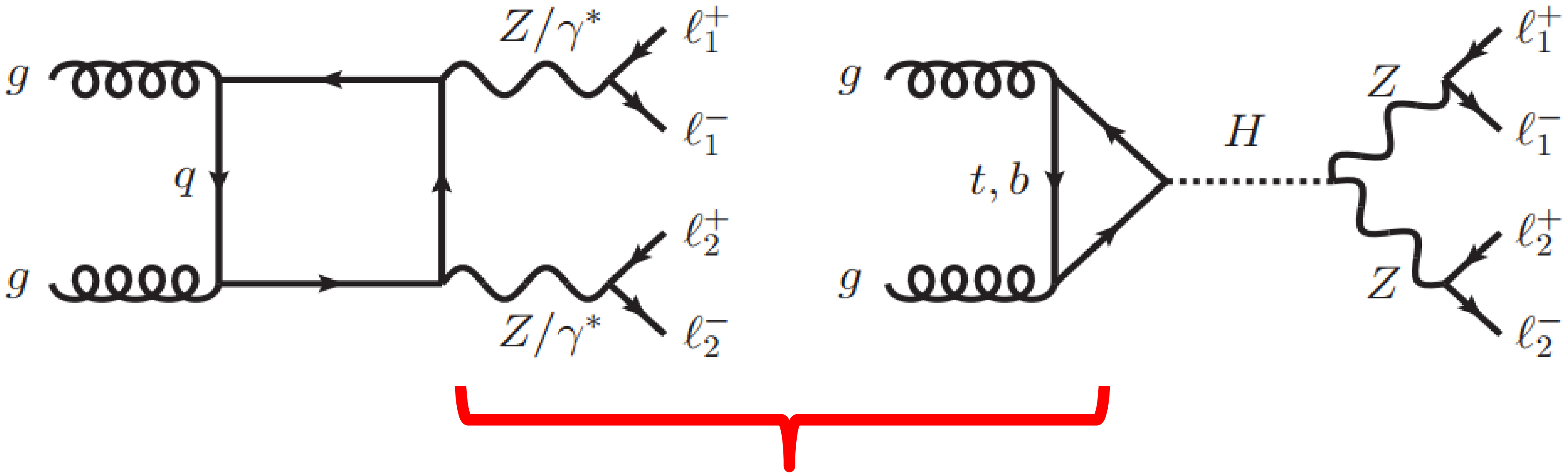
$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p^2_{T,\,\mathrm{jet}}}{m^2_Z}$$

NNLO



VV@NNLO

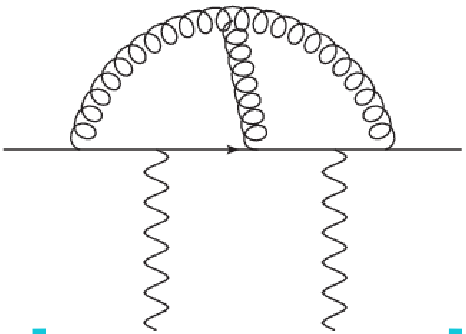
- Neutral Processes

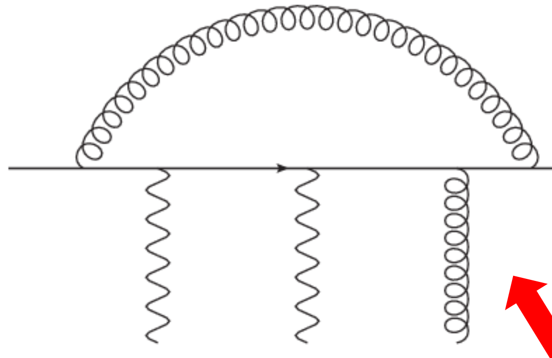


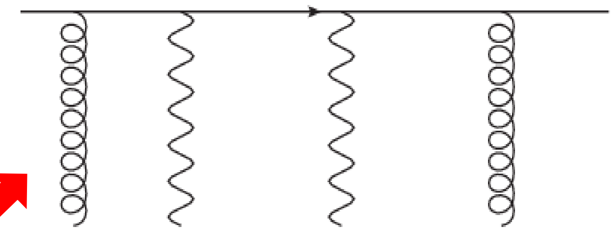
GF ZZ at LO

- LO Kinematics, but gluon PDF's

VV@NNLO







$$\mathcal{O}\left(\alpha_s^2 \sigma_{\mathrm{LO}}^{(A)}\right)$$

$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p^2_{T,\mathrm{jet}}}{m_Z^2}$$

VVj at NLO

- IR divergences upon parton integration
- How to exploit the known NLO results for VV + n jets?
  - Merging: Sherpa, Herwig++, MG5_aMC@NLO

LoopSim (M.Rubin,G.Salam,S.Sapeta,ArXiv:1006.2144)

Goal

- Merge processes with different multiplicity: VV, VVj,VVj j
- Include dominant contributions of extra emissions, possibly log enhance

Method

X $@\mathrm{NLO}$

X$j@\mathrm{NLO}$

Loop X$j@\mathrm{NLO}$ (Catani-Seymour like generated of loop kinematics)

$$\begin{array}{lcccc} V_1 \dots V_n @\mathrm{LO} & + & V_1 \dots V_n j @\mathrm{LO} & \rightarrow & V_1 \dots V_n @\bar{n}\mathrm{LO} \\ V_1 \dots V_n @\mathrm{NLO} & + & V_1 \dots V_n j @\mathrm{NLO} & \rightarrow & V_1 \dots V_n @\bar{n}\mathrm{NLO} \end{array}$$

Inspired by CKKW matching

LoopSim

(M.Rubin,G.Salam,S.Sapeta,ArXiv:1006.2144)

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Goal

- Merge processes with different multiplicity: VV, VVj,VVjj
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X $@\mathrm{NLO}$
X$j@\mathrm{NLO}$
Loop X$j@\mathrm{NLO}$ (Catani-Seymour like generated of loop kinematics)

$$V_1 \ldots V_n@\mathrm{NLO} \quad + \quad V_1 \ldots V_n j@\mathrm{NLO} \\ + \quad V_1 \ldots V_n jj@\mathrm{NLO} \quad \rightarrow \quad V_1 \ldots V_n@\bar{n}\bar{n}\mathrm{NLO}$$

Inspired by CKKW matching

ZZ@nNLO

(FC,M.Rauch,S.Sapeta:ArXiv:1504.05588)

- VBFNLO: ZZ@NLO, ZZj@NLO, GFZZ@LO and GFZZj@LO [FC,Q.Li,M.Rauch,M.Spira,1211.5429] (NNNLO)

σ_{LO} [pb]	$5.0673(4)\ ^{+1.6\%}_{-2.7\%}$	(*Ref. [32]*: $5.060\ ^{+1.6\%}_{-2.7\%}$)
σ_{NLO} [pb]	$7.3788(10)\ ^{+2.8\%}_{-2.3\%}$	(*Ref. [32]*: $7.369\ ^{+2.8\%}_{-2.3\%}$)
$\sigma_{\mathrm{NLO+LO\text{-}GF}}$ [pb]	$7.946(3)\ ^{+4.2\%}_{-3.2\%}$	
σ_{NNLO} [pb]		(*Ref. [32]*: $8.284\ ^{+3.0\%}_{-2.3\%}$)
$\sigma_{\bar{n}\mathrm{NLO}}$ [pb]	$8.103(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	
$\sigma_{\bar{n}\mathrm{NLO}+\bar{n}\mathrm{LO\text{-}GF}}$ [pb]	$8.118(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	

Ref.[32]: F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhfer, A. von Manteuffel, S. Pozzorini et al.,arXiv:1405.2219

- GF 60% of total NNLO corrections
- nNLO vs NNLO 2%: within scale uncertainties

Anomalous Coupling Searches

PDF set: MSTW2008 at NNLO

Scale:

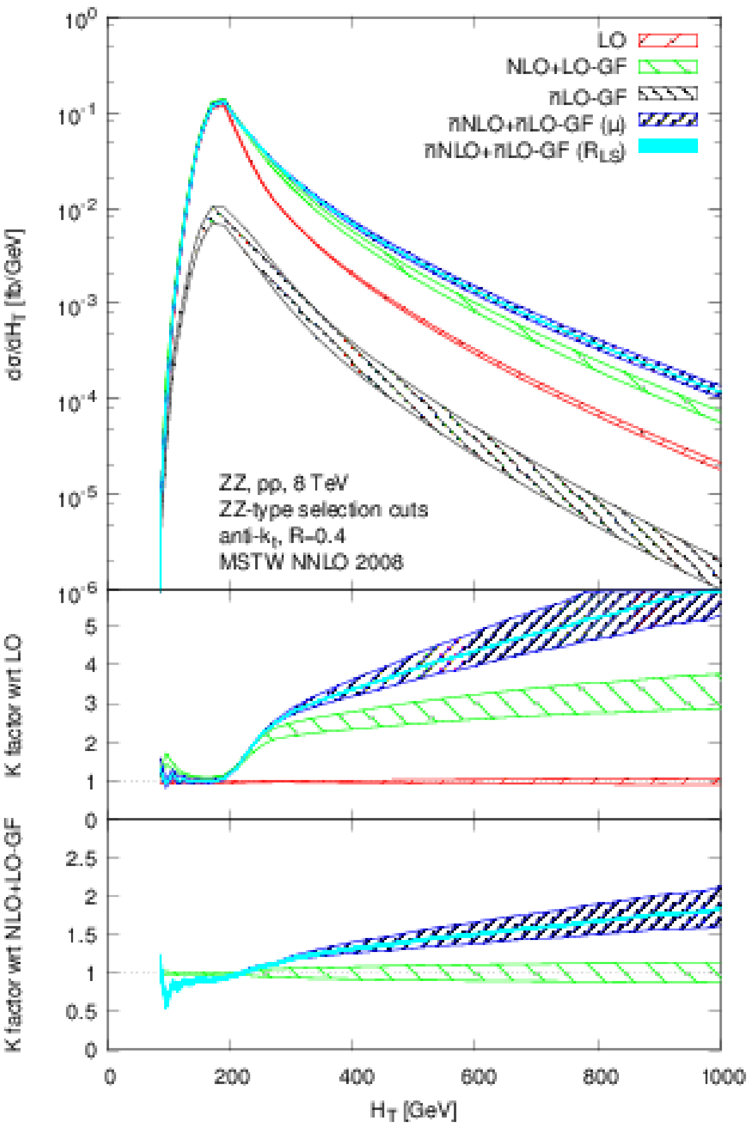
$$\mu_{F,R} = \mu_0 = \frac{1}{2}\left(\sum p_{T,\text{partons}} + \sqrt{p_{T,V_1}^2 + m_{V_1}^2} + \sqrt{p_{T,V_2}^2 + m_{V_2}^2}\right)$$

$$\begin{aligned} p_{t,\ell} &> 20\,\text{GeV}\,, & |\eta_\ell| &< 2.5\,, \\ p_{t,\,\text{jet}} &> 25\,\text{GeV}\,, & |\eta_{\text{jet}}| &< 4.5\,, \\ \Delta R_{\ell,\,\text{jet}} &> 0.3\,, & \Delta R_{\ell,\ell} &> 0.2\,. \end{aligned}$$

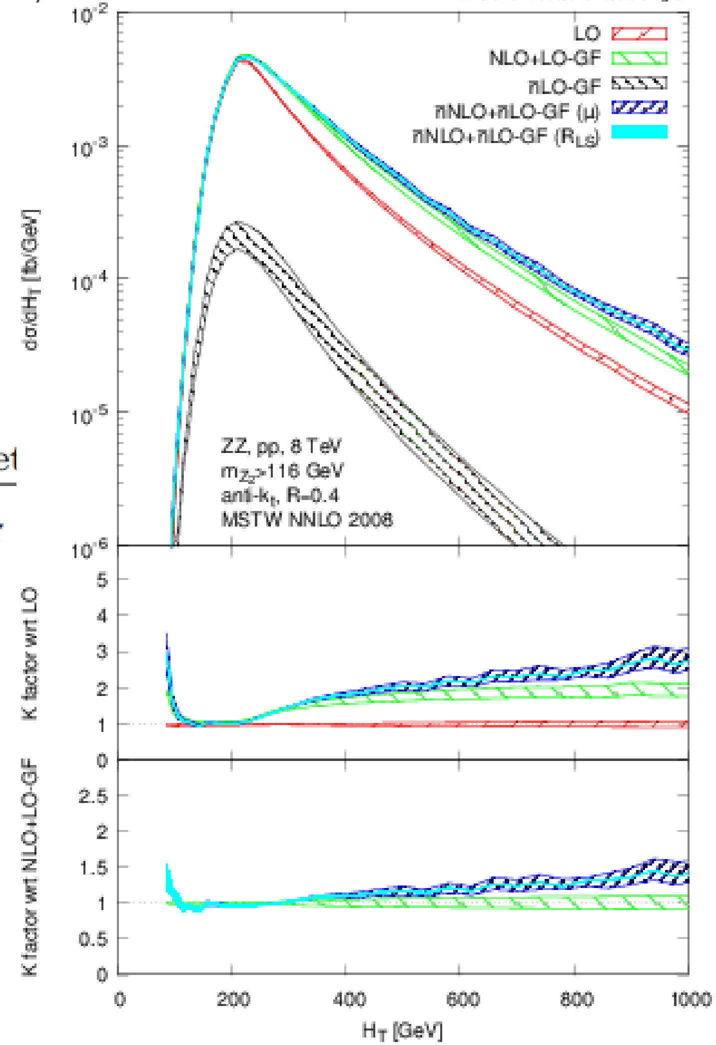
ZZ selection: $m_{Z_1}, m_{Z_2} \in (66, 116)\,\text{GeV}\,,$

ZZ^* selection: $m_{Z_1} \in (66, 116)\,\text{GeV}\,,\ m_{Z_2} \in (20, 66) \cup (166, m_{Z,\text{max}})\,\text{GeV}\,,$

$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,l}$$



$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\text{jet}}^2}{m_Z^2}$$



$$m_{Z_2} \in (166, m_{Z,\max})\ \text{GeV}$$

WW@nNLO

(FC,M.Rauch,S.Sapeta:ArXiv:1309.7293)

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- VBFNLO: WW@NLO, WWj@NLO, GF WW@LO
  - W^+W^- decaying to: $l_1^-\bar{\nu}_{l_1} l_2^+\nu_{l_2}$ and $l^-\bar{\nu}_l l^+\nu_l$
  - PDFs: MSTW NNLO 2008
  - $\mu_{F,R} = \frac{1}{2}\left\{\sum p_{T,partons} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,W}^2 + m_W^2}\right\}$
  - Cuts:

$$|y_l| < 2.5, \qquad p_{T_l} > 20\mathrm{GeV}$$

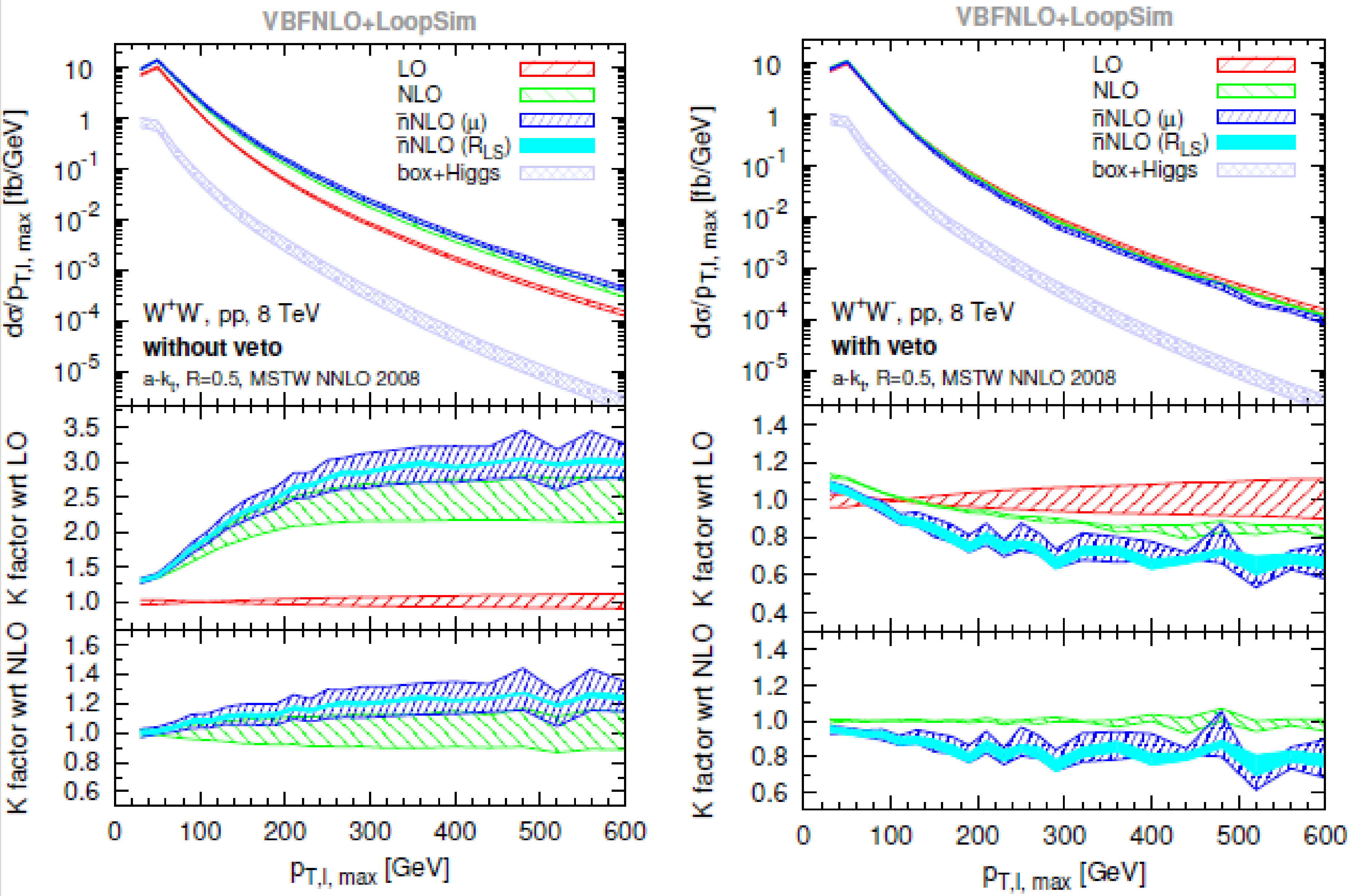
$$\mathrm{anti}-k_t, R = 0.45$$

$$|\eta_{\mathrm{jet}}| < 4.5 \quad p_{T_{\mathrm{jet}}} > 15\ \mathrm{GeV}$$

$$E_{Tprojectedmiss} > 20(45) GeV$$

$$m_{ll} > 12\mathrm{GeV}, \qquad |m_{ll} - M_Z| > 15\mathrm{GeV}$$

$$|\Delta(\phi_{ll} - \phi_{\mathrm{hardestjet,pt}>15})| < 165$$


VBFNLO+LoopSim
LO
NLO
n̄NLO (μ)
n̄NLO (R_LS)
box+Higgs
W+W-, pp, 8 TeV
without veto
a-kt, R=0.5, MSTW NNLO 2008
dσ/pT,l, max [fb/GeV]
K factor wrt LO
K factor wrt NLO
pT,l, max [GeV]
VBFNLO+LoopSim
W+W-, pp, 8 TeV
with veto
a-kt, R=0.5, MSTW NNLO 2008

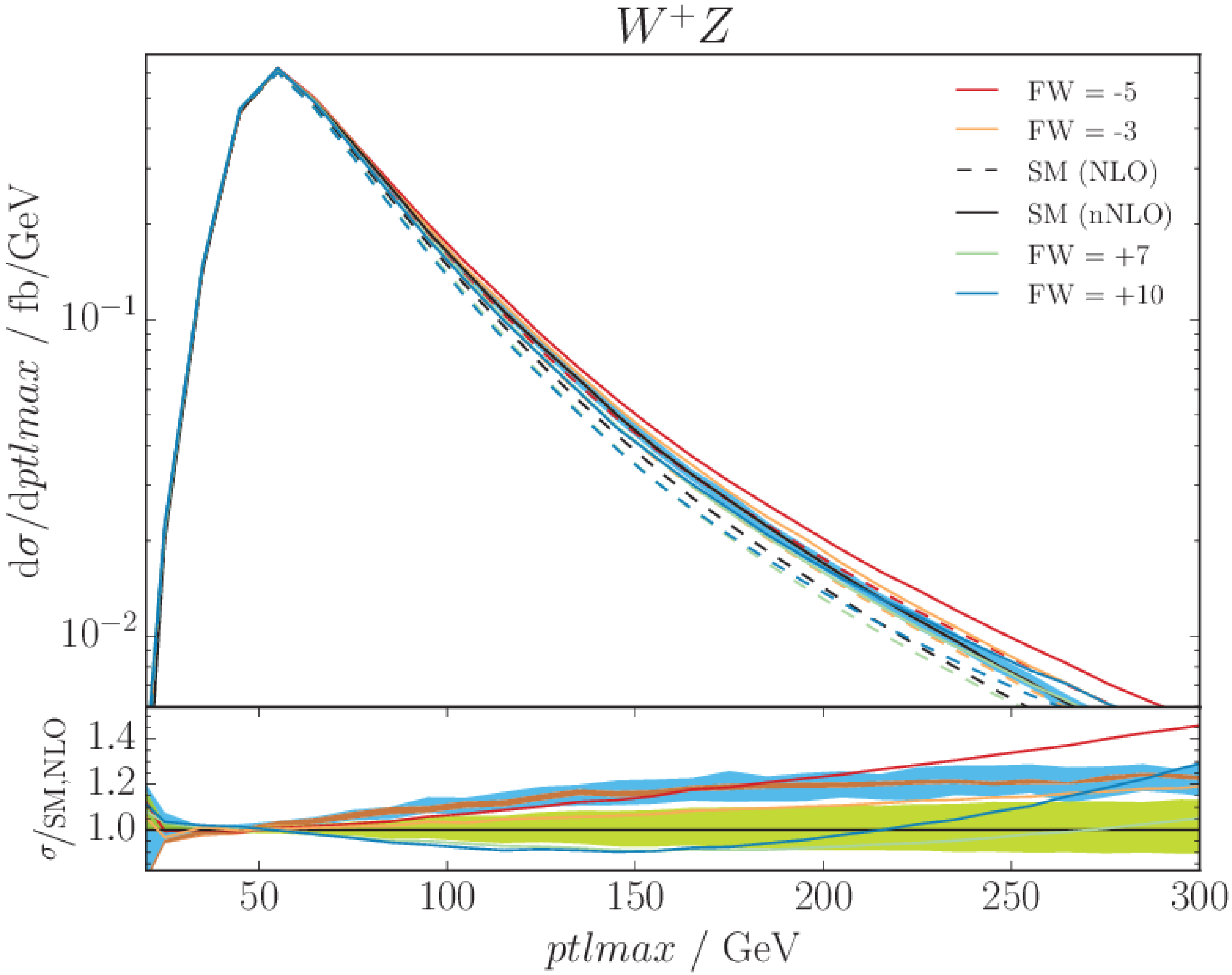
WZ@nNL

(FC,S.Sapeta:ArXiv:1209.4595)

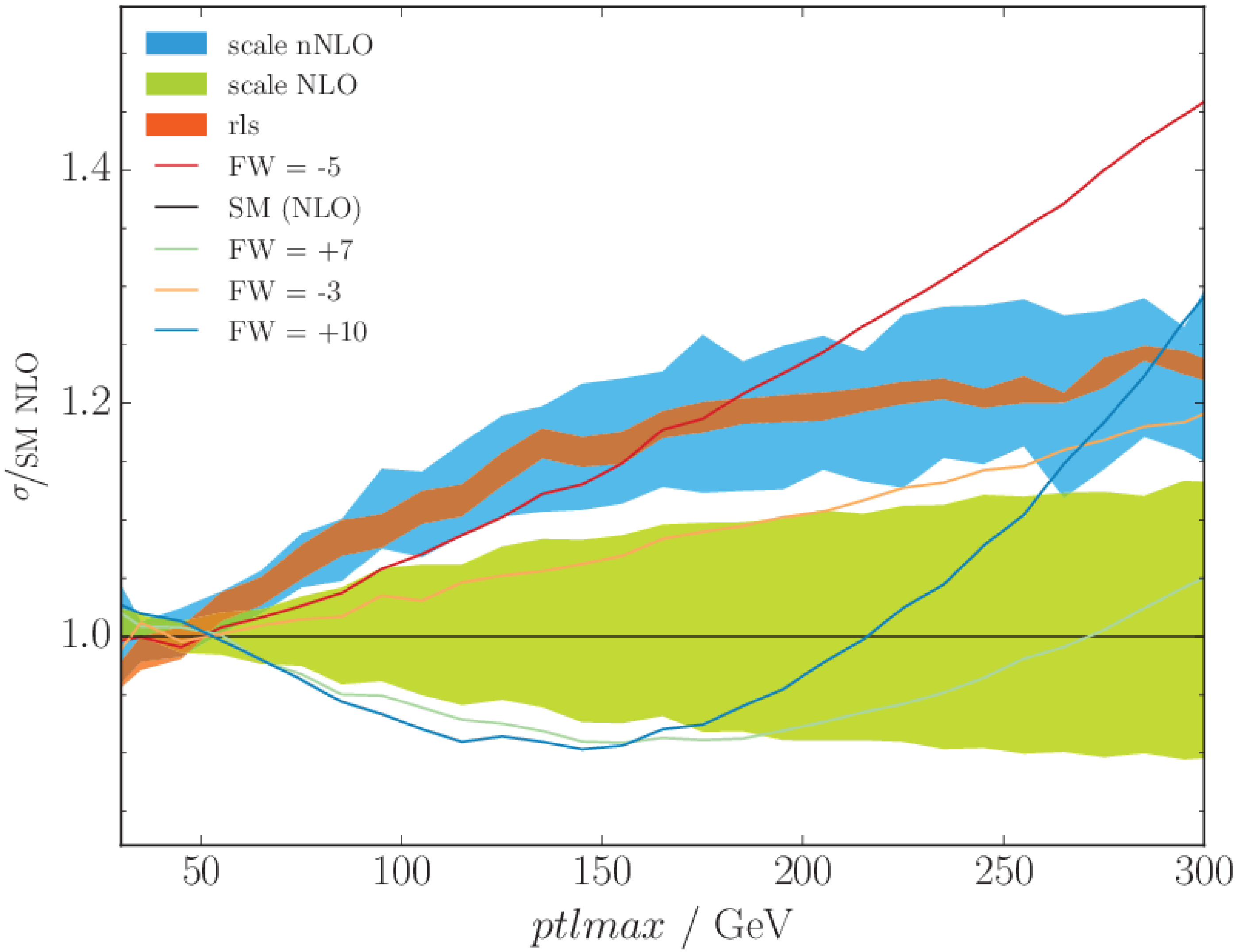
- VBFNLO: WZ@NLO, WZj@NLO, (FC,S.Kallweit,C.Englert,Spannowsky, Zeppenfeld,ArXiv:1006.0390)
  - W^+Z and W^-Z channels decaying to: $ee\mu\nu_\mu$ and $\mu\mu e\nu_e$
  - PDFs: MSTW NNLO 2008
  - $\mu_{F,R} = \frac{1}{2}\left\{\sum p_{T,partons} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,Z}^2 + m_Z^2}\right\}$
  - Cuts:

$$|y_l| < 2.5, \qquad p_{T_l} > 15(20)\mathrm{GeV}$$
$$60 < m_{ll} < 120\mathrm{GeV}$$
$$E_{Tmiss} > 30 GeV$$
$$\mathrm{anti} - k_t,\ R = 0.45$$
$$|\eta_{\mathrm{jet}}| < 4.5 \qquad p_{T_{\mathrm{jet}}} > 30\ \mathrm{GeV}$$
$$R_{ll(j)} > 0.3$$

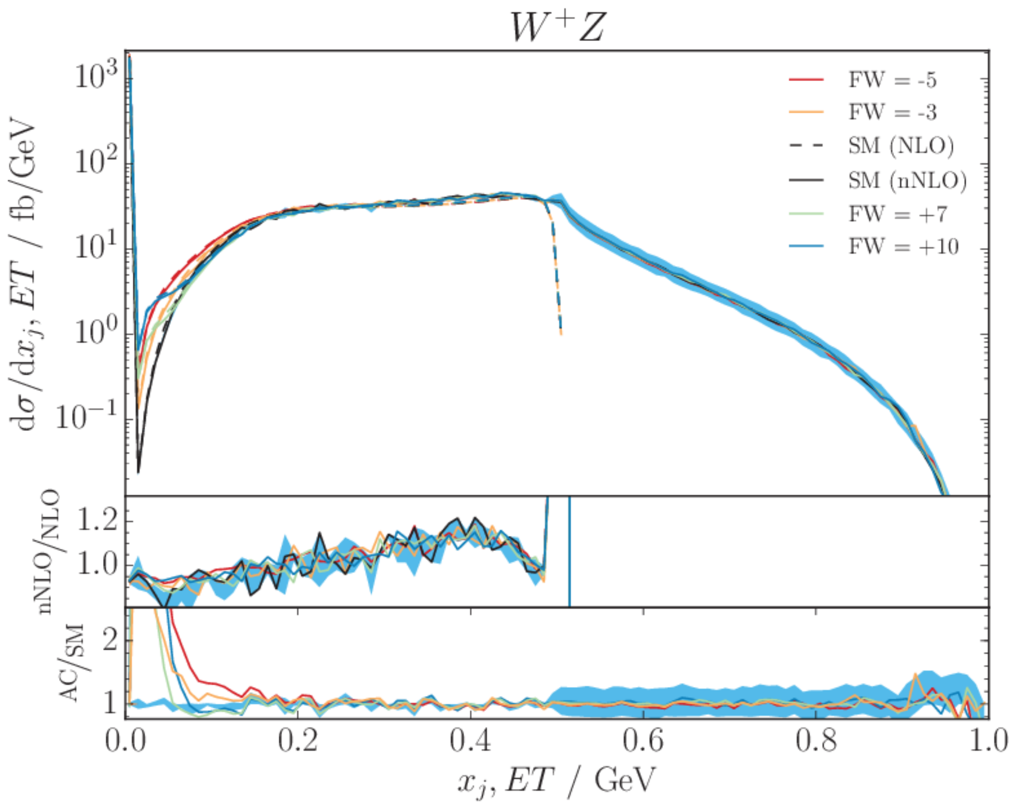
NNLO QCD fakes AC effects (FC,R.Roth,S.Sapeta,Zeppenfeld)



NNLO QCD fakes AC effects

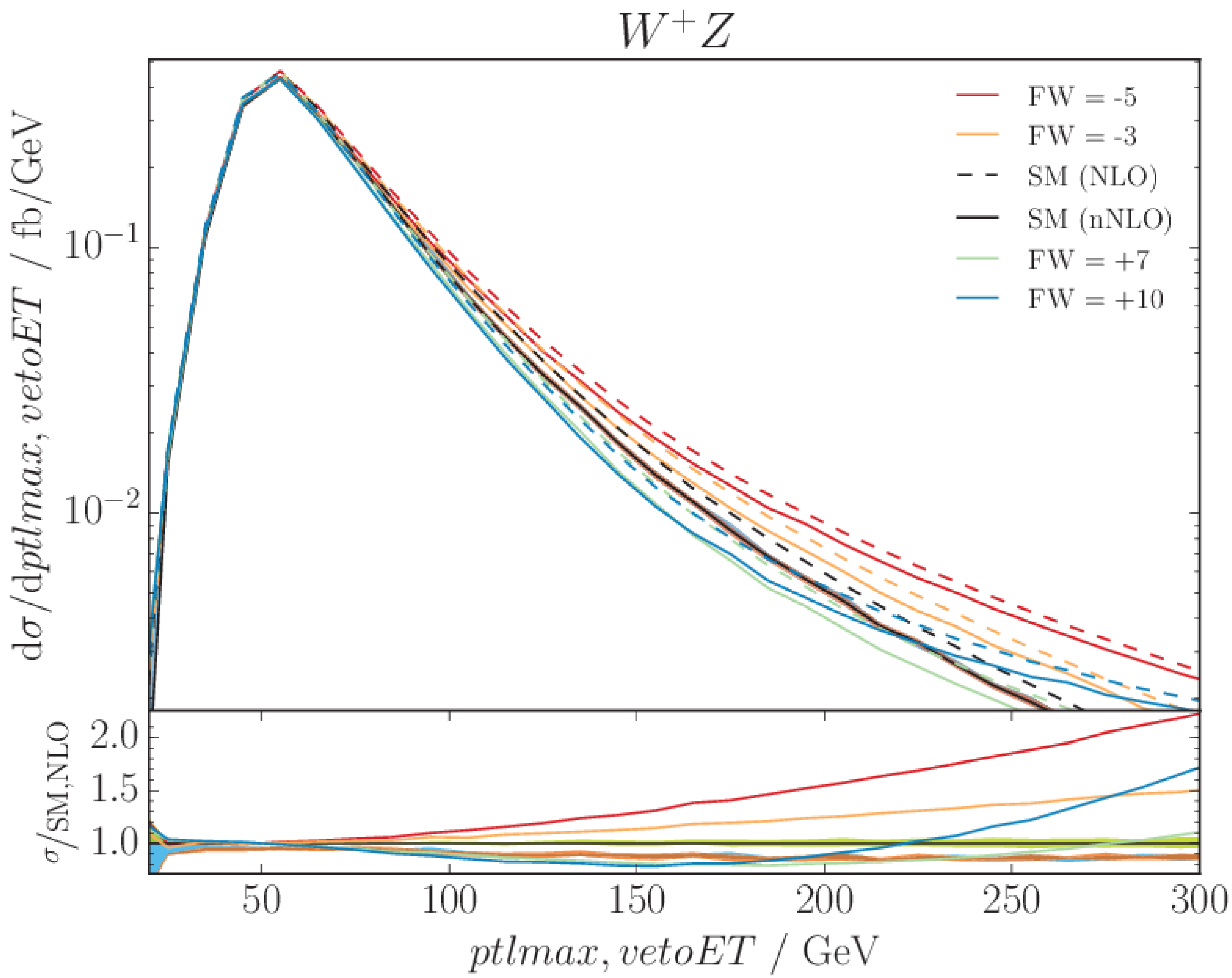


Jet Observable (FC,R.Roth,Zeppenfeld:ArXiv:1410.4840)



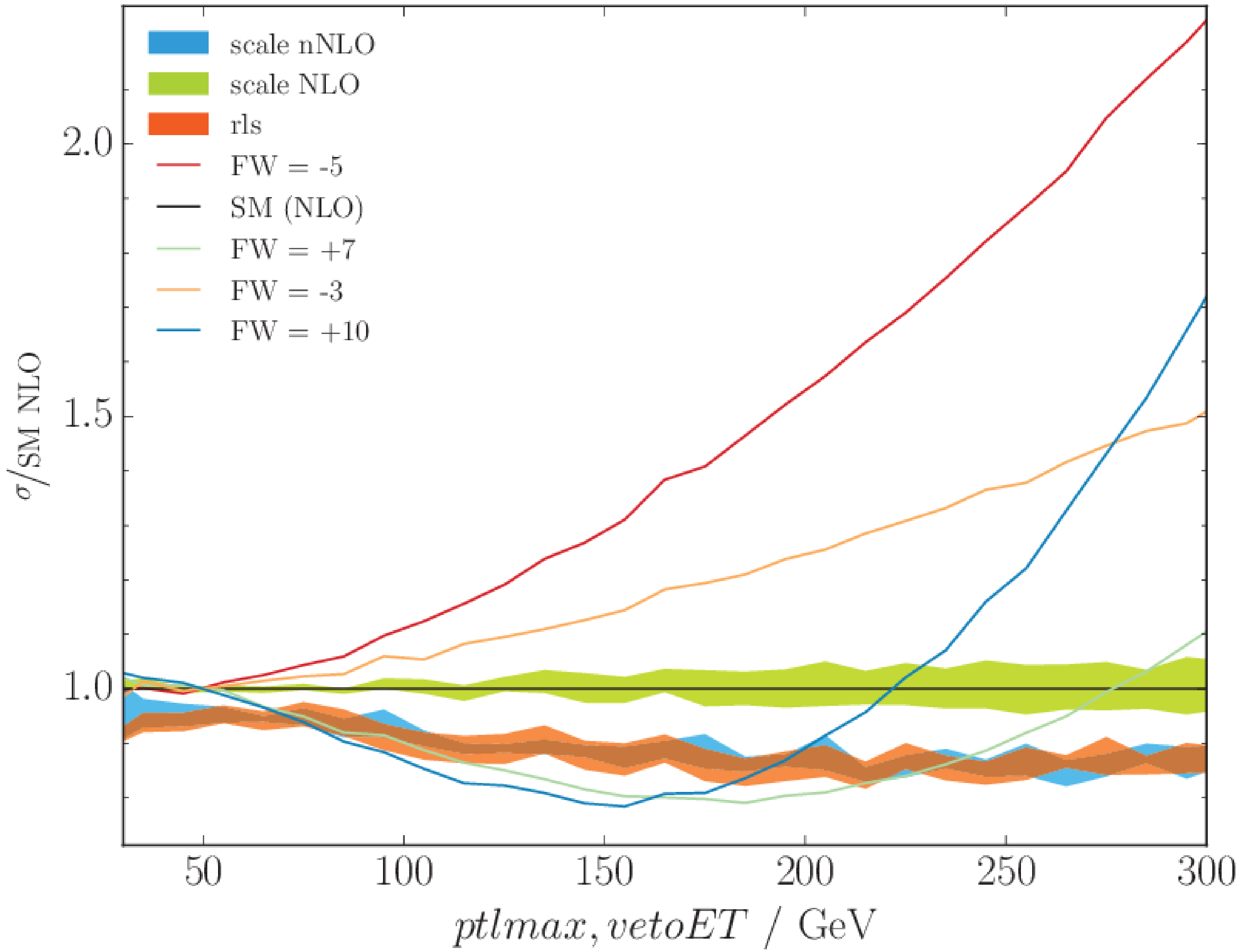
$$x_{\text{jet}} = \frac{\sum_{k\in\{\text{jets}\}} E_{T,k}}{\sum_{k\in\{\text{jets,Zs}\}} E_{T,k}}$$

WZ@nNLO + AC



W^+Z
FW = -5
FW = -3
SM (NLO)
SM (nNLO)
FW = +7
FW = +10
$\mathrm{d}\sigma/\mathrm{d}ptlmax, vetoET$ / fb/GeV
10^{-1}
10^{-2}
$\sigma/_{\mathrm{SM,NLO}}$
2.0
1.5
1.0
50
100
150
200
250
300
$ptlmax, vetoET$ / GeV

WZ@nNLO + AC


scale nNLO
scale NLO
rls
FW = -5
SM (NLO)
FW = +7
FW = -3
FW = +10
σ/SM NLO
2.0
1.5
1.0
50
100
150
200
250
300
ptlmax, vetoET / GeV

References VV@LHC

VBFNLO:

https://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=overview

LoopSim:

https://loopsim.hepforge.org/

NNLO QCD

- γγ :Catani, Cieri, de Florian, Ferrera, Grazzini 2011]
- W γ /Zγ: Grazzini, Kallweit, Rathlev, Torre 2013, Grazzini, Kallweit, Rathlev 2015
- ZZ :Cascioli et al. '14, Grazzini, Kallweit, Rathlev 2015
- WW: [Gehrmann et al. 2014

GF LO

- γγ: D. A. Dicus and S. S. D. Willenbrock, Phys. Rev. D 37 (1988) 1801
- Zγ : J. J. van der Bij and E. W. N. Glover, Phys. Lett. B206 (1988) 701,
- ZZ: . E. Glover and J. van der Bij, Phys.Lett. B219 (1989) 488
- WW: T. Binoth, M. Ciccolini, N. Kauer and M. Kramer, JHEP 12 (2006) 046.

NLO EW(on-shell):

- WW/WZ: E. Accomando and A. Kaiser, Phys.Rev. D73 (2006) 093006.
- W γ / Zγ: E. Accomando, A. Denner, and C. Meier, Eur.Phys.J.C47 (2006) 125–146
- ZZ A. Bierweiler, T. Kasprzik, and J. H. Kühn,arXiv:1305.5402, J.Baglio, N.D.Li, M. Weber Phys. Rev.D 88 (2013) 113005.

Summary

Total Cross section:

- Good agreement for ZZ at NNLO (not compared for other)

Differential Distributions

- Corrections can be large 30-100%
- Observable favoring LO kinematics: 5%
- (GF)ZZ@nLO: 50% corrections

Anamolous Couplings

- NNLO can fake AC effects
- More sophisticated analyses are needed to increase sensitivity

Outlook:

VV@nNLO+AC, VV@nnNLO, VVV@nNLO

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THANK YOU FOR YOUR ATTENTION

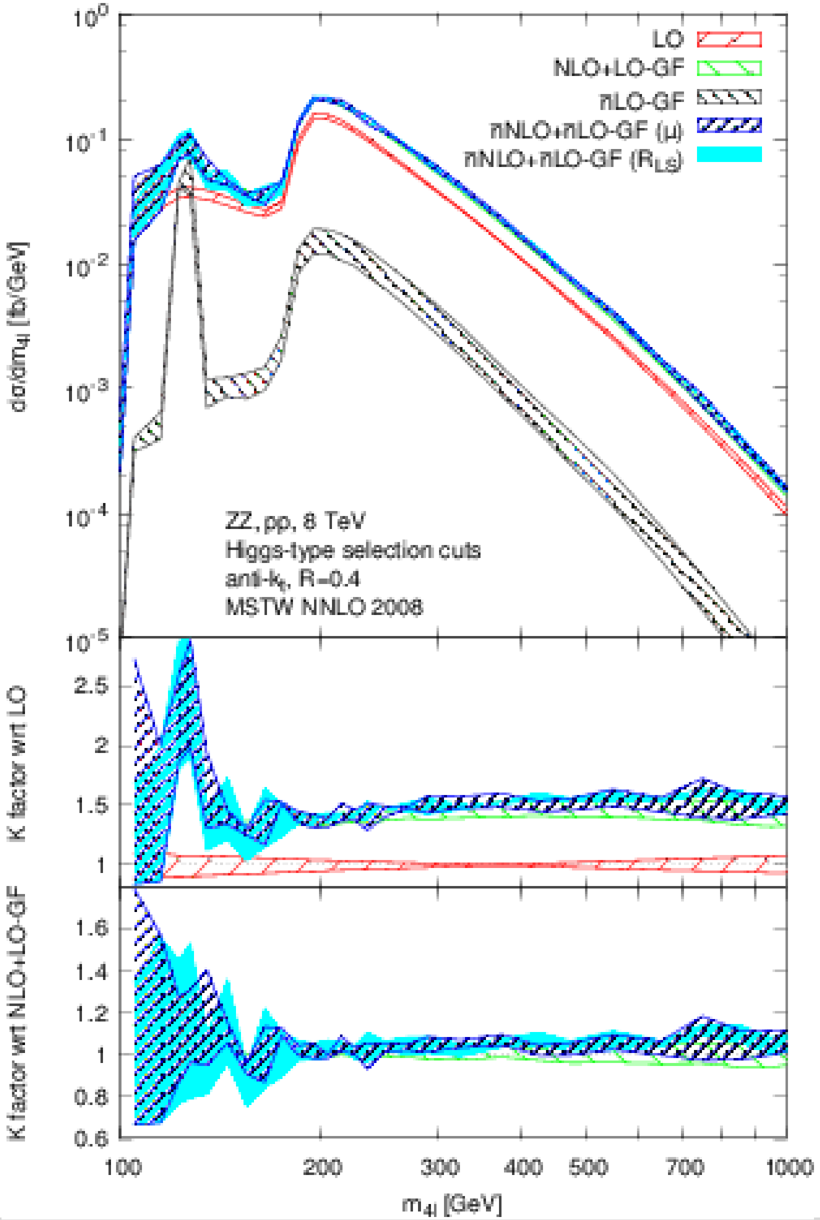
Backup Slides

Higgs Searches

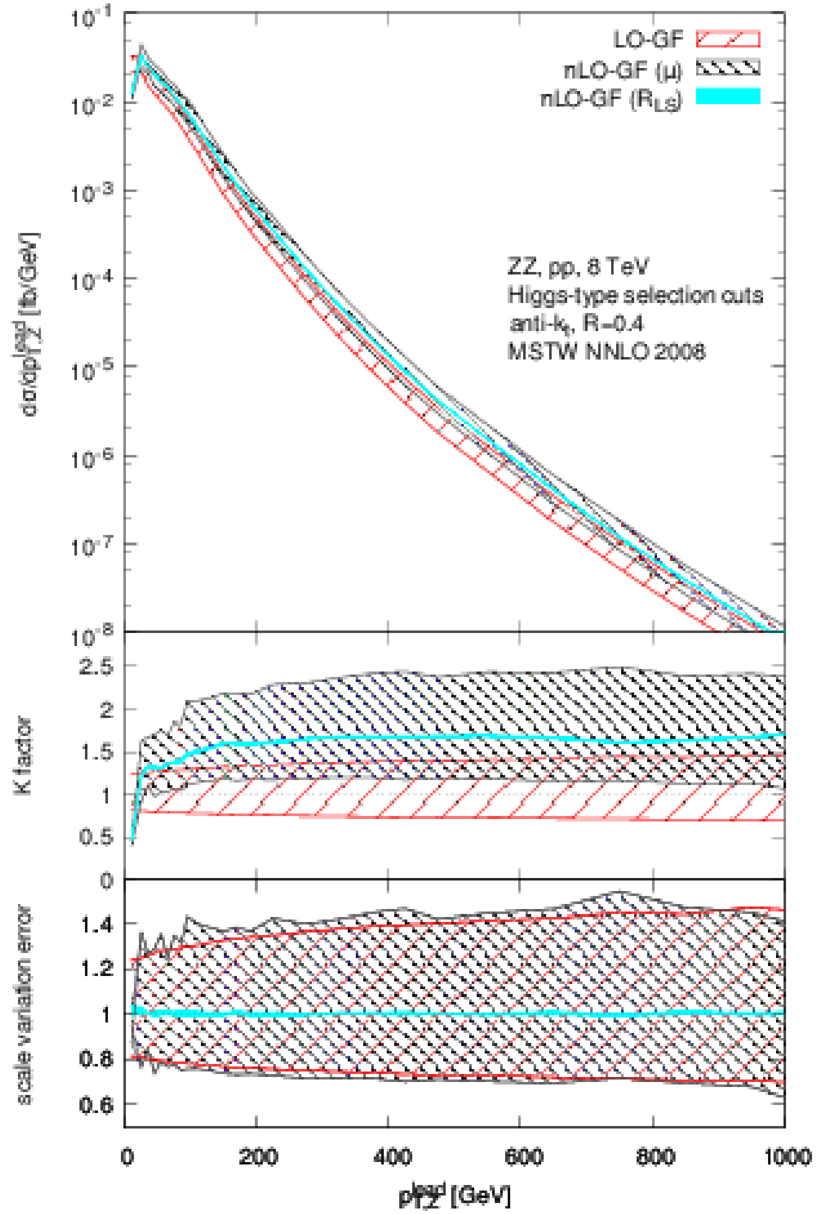
$$p_{t,e} > 7\,\text{GeV}\,, \qquad |\eta_e| < 2.5\,,$$
$$p_{t,\mu} > 5\,\text{GeV}\,, \qquad |\eta_\mu| < 2.4\,,$$
$$p_{t,\ell_{\text{hardest}}} > 20\,\text{GeV}\,, \qquad m_{4\ell} > 100\,\text{GeV}\,,$$
$$p_{t,\ell_{\text{second-hardest}}} > 10\,\text{GeV}\,,$$

$$40 < m_{\ell\ell} < 120\,\text{GeV} \qquad \text{for the } \ell\ell \text{ pair with mass closer to } m_Z,$$
$$12 < m_{\ell\ell} < 120\,\text{GeV} \qquad \text{for the other } \ell\ell \text{ pair},$$
$$m_{\ell\ell} > 4\,\text{GeV} \qquad \text{for any oppositely-charged pair of leptons.}$$

M_{4l} & $p_{T,Z}^{lead}$

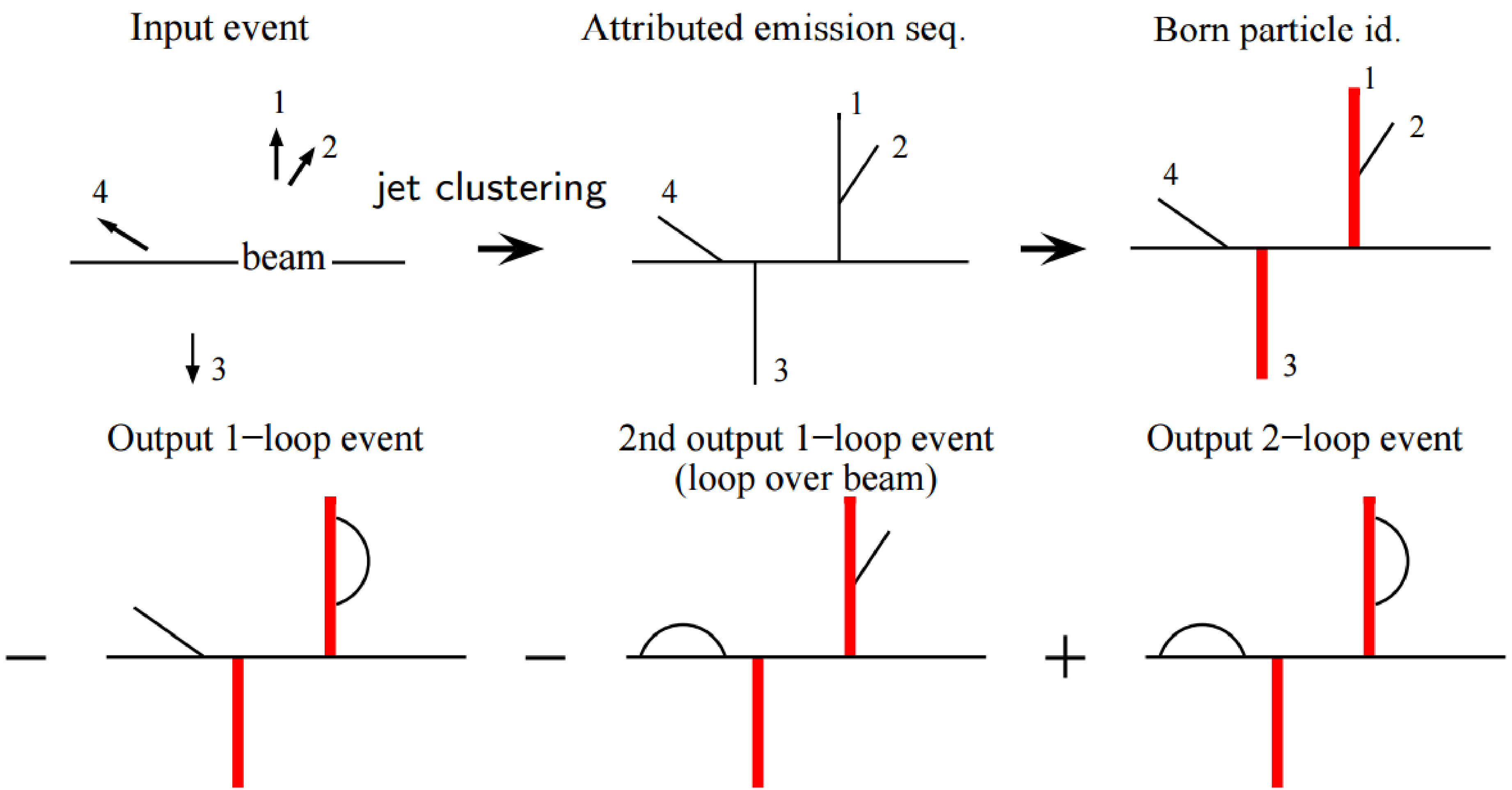


LO
NLO+LO-GF
ñLO-GF
ñNLO+ñLO-GF (μ)
ñNLO+ñLO-GF (R_LS)
ZZ, pp, 8 TeV
Higgs-type selection cuts
anti-k_t, R=0.4
MSTW NNLO 2008
dσ/dm_4l [fb/GeV]
K factor wrt LO
K factor wrt NLO+LO-GF
m_4l [GeV]



LO-GF
ñLO-GF (μ)
ñLO-GF (R_LS)
ZZ, pp, 8 TeV
Higgs-type selection cuts
anti-k_t, R=0.4
MSTW NNLO 2008
K factor
scale variation error
p_T,Z^lead [GeV]

LoopSim



Sum of weights = 0 (Unitarity)

Ingredients

VBFNLO:

ZZ@NLO ZZj@NLO

GF ZZ@LO GF ZZj@LO

Note that GF ZZ@LO contributes at NNLO and

GF ZZj@LO contributes at NNNLO

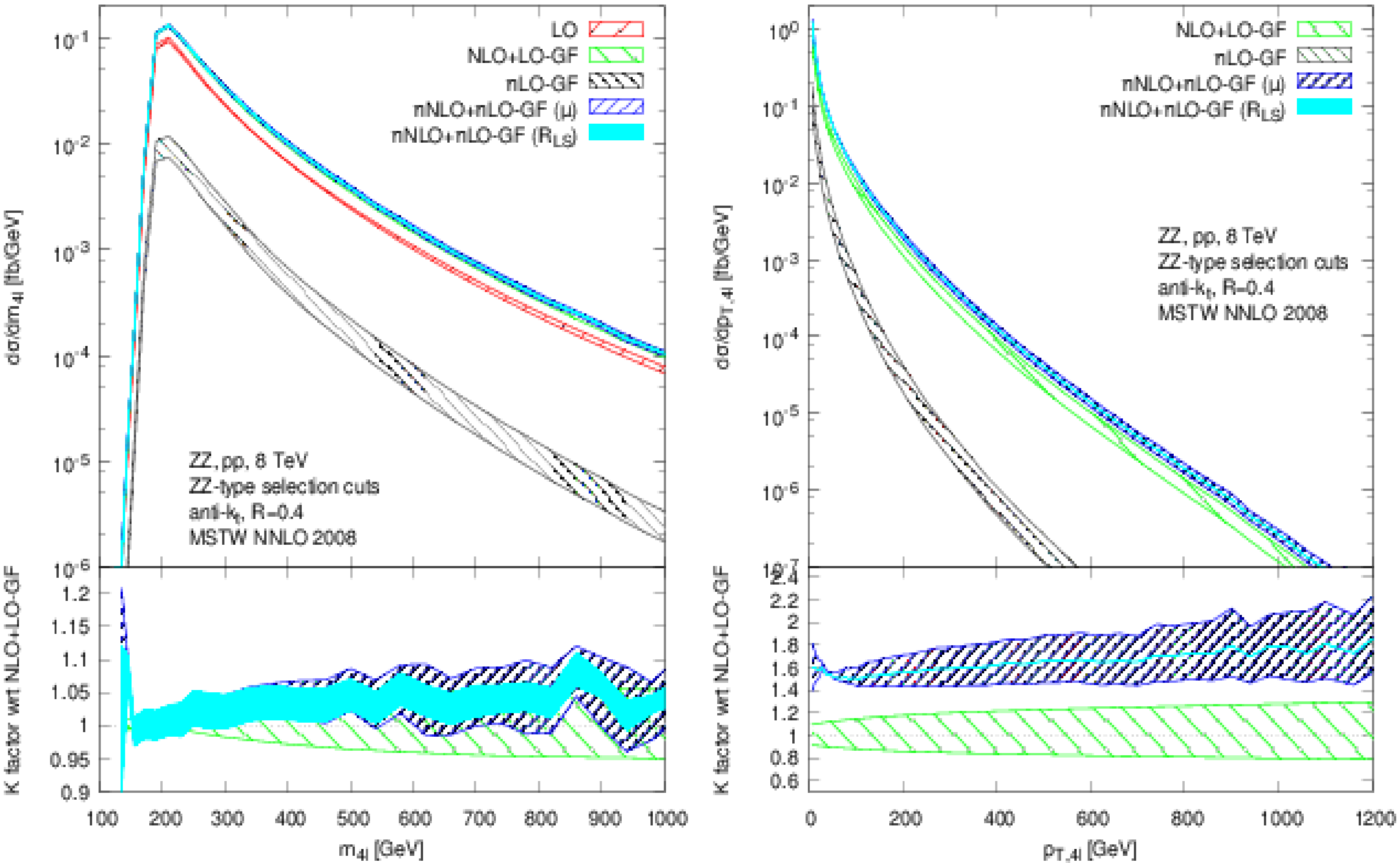
Merging Convention:

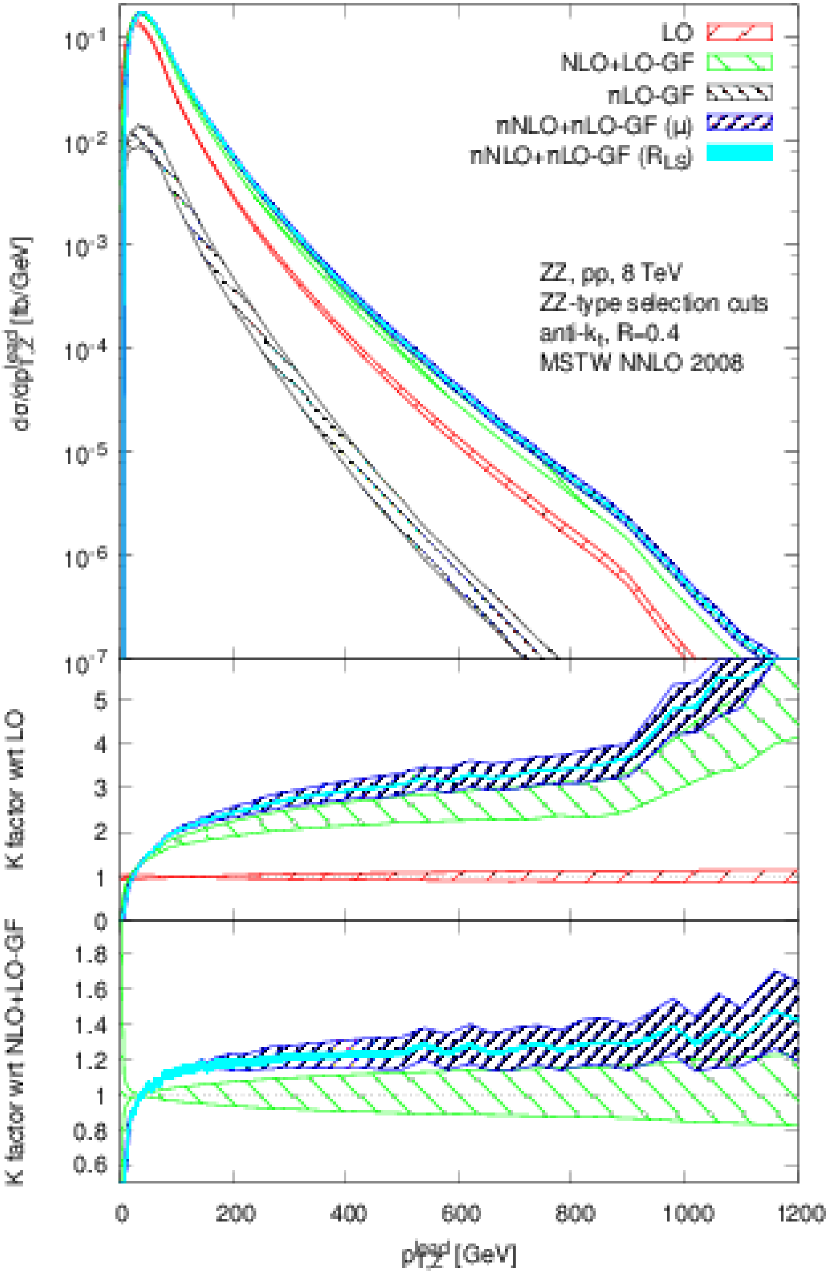
GF ZZ@LO + GF ZZj@LO = GF ZZ@nLO

ZZ@NLO + ZZj@NLO + GF ZZ@LO = ZZ@nNLO

ZZ

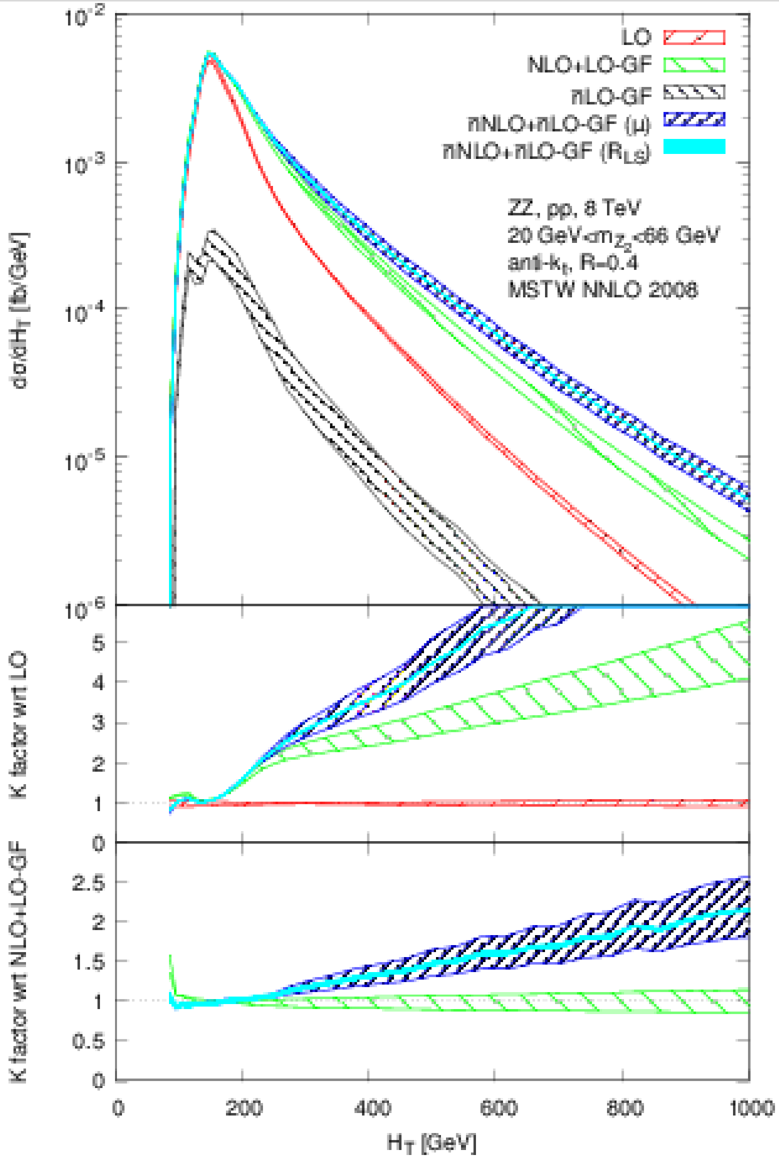
4 lepton observables



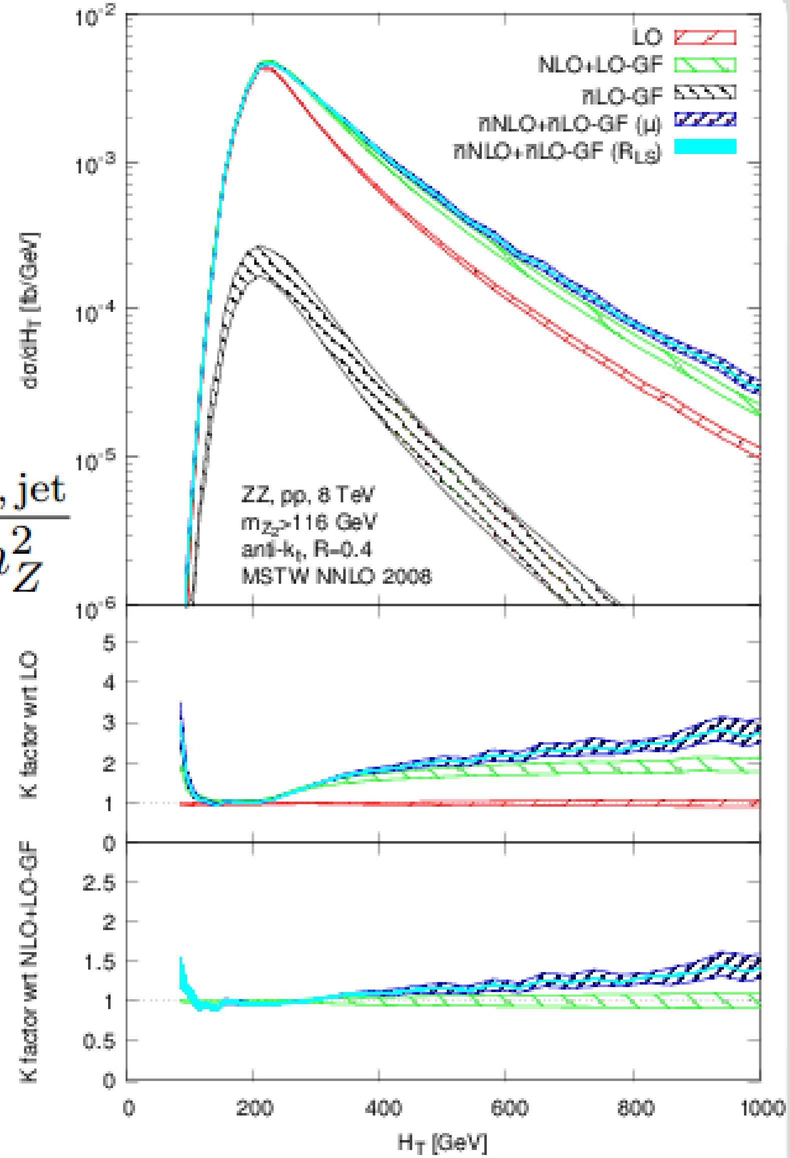


$$m_{\ell\ell}^2 \simeq \frac{1}{4} p_{T,Z}^2 \Delta R_{\ell,\ell}^2$$

$$p_{T,Z} \lesssim 10\, m_{\ell\ell}$$



$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\mathrm{jet}}^2}{m_Z^2}$$



$m_{Z_2} \in (20, 66)\,\mathrm{GeV}$ $m_{Z_2} \in (166, m_{Z,\max})\,\mathrm{GeV}$

$$H_T = \sum p_{T,\mathrm{jets}} + \sum p_{T,l}$$

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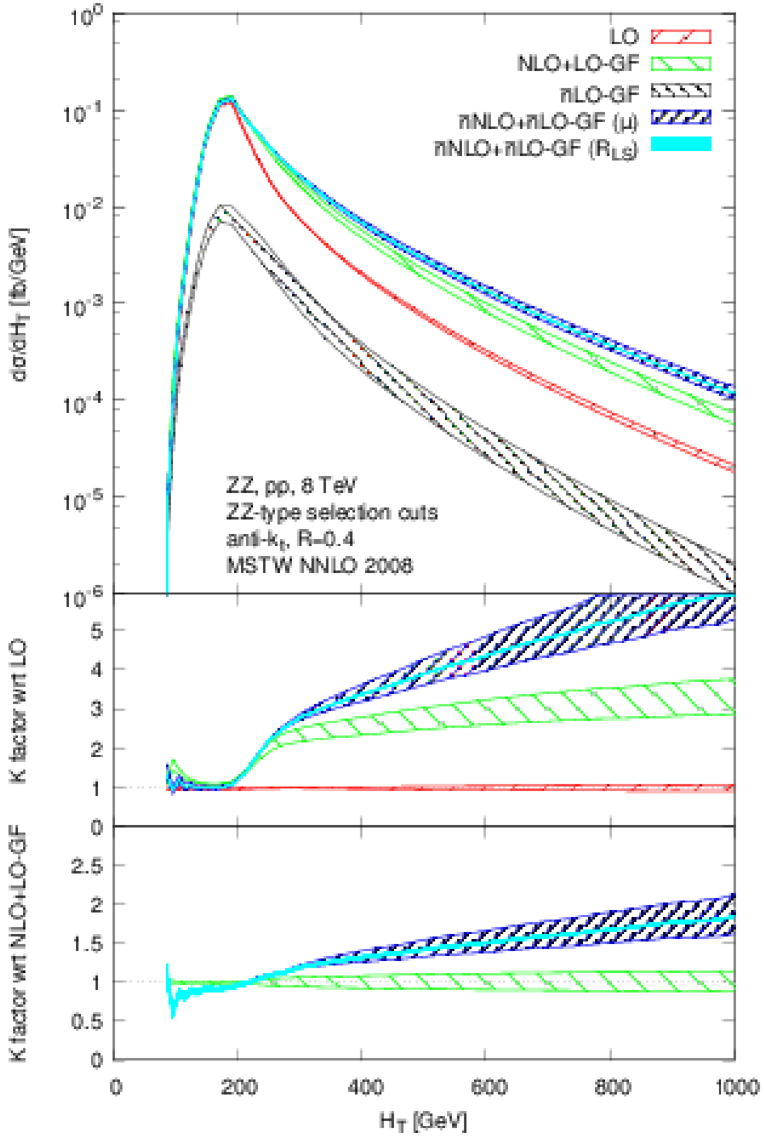
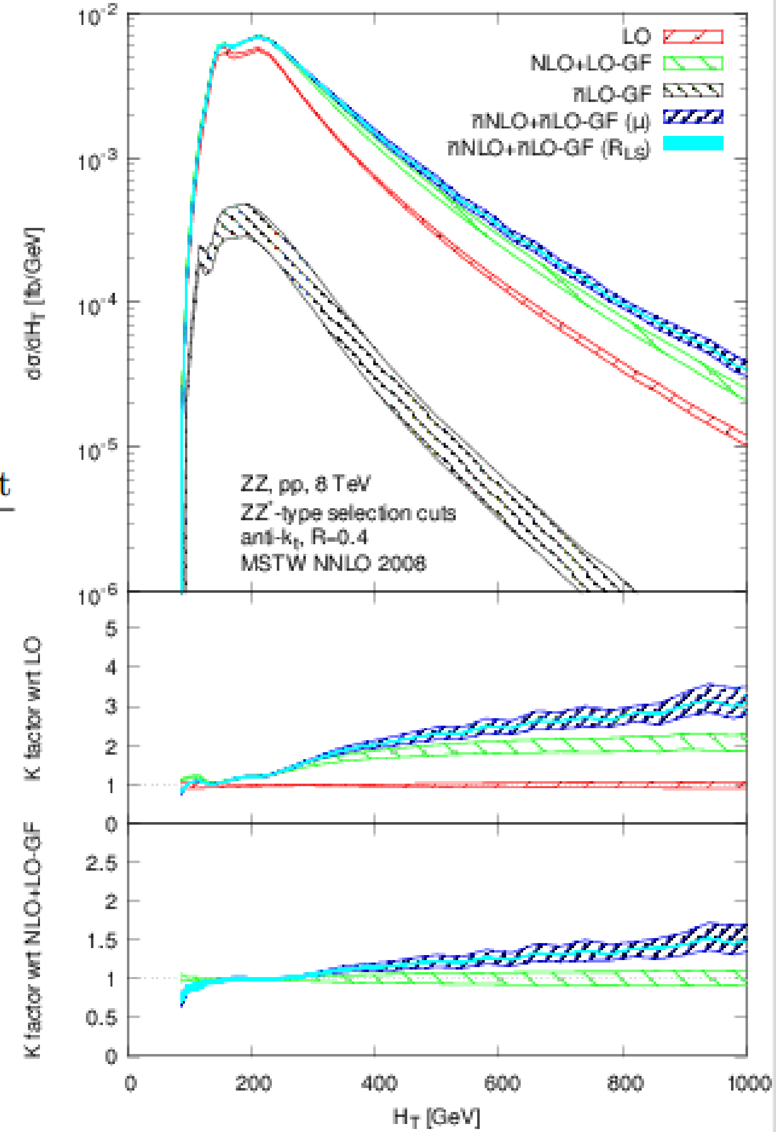
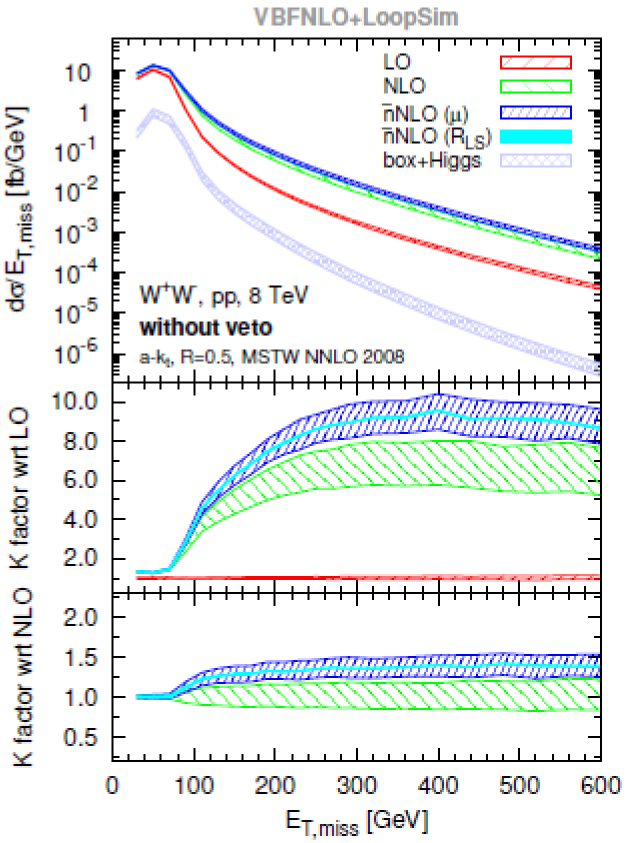


$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p^2_{T,\,\mathrm{jet}}}{m_Z^2}$$



WW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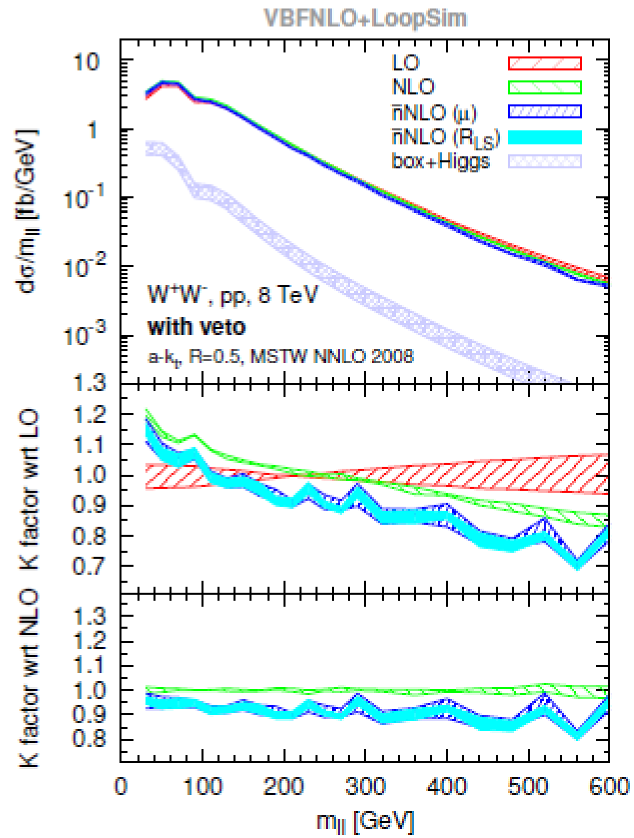
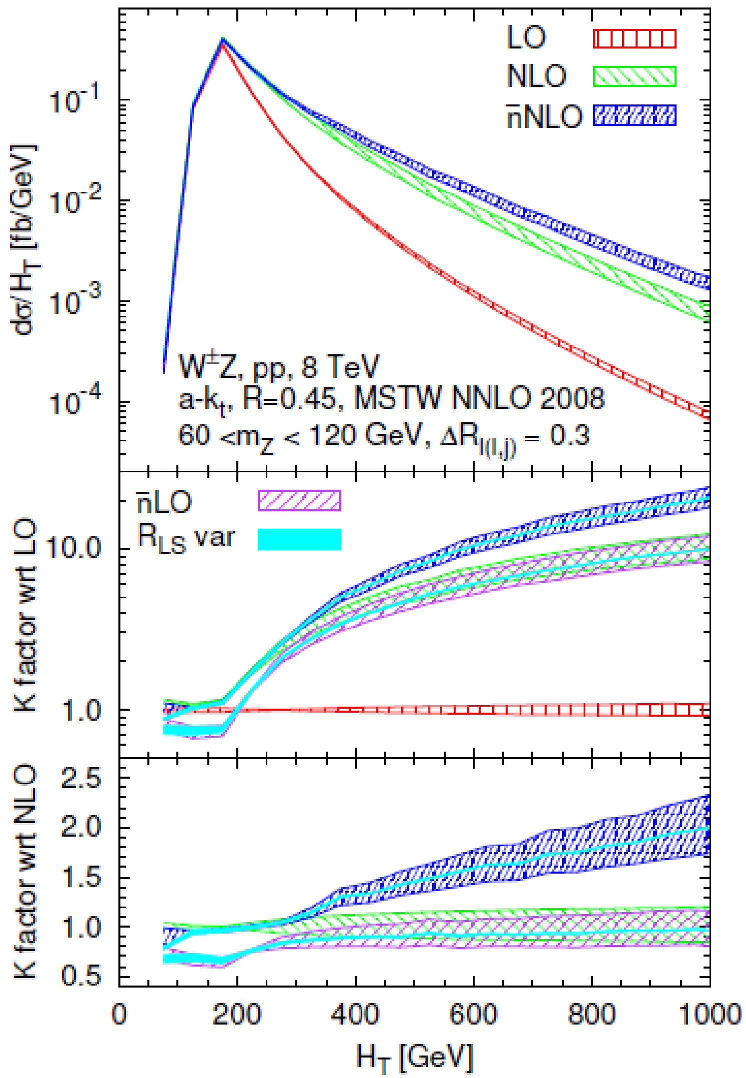
a-kt, R=0.5, MSTW NNLO 2008
dσ/$E_{T,miss}$ [fb/GeV]
K factor wrt LO
K factor wrt NLO
$E_{T,miss}$ [GeV]

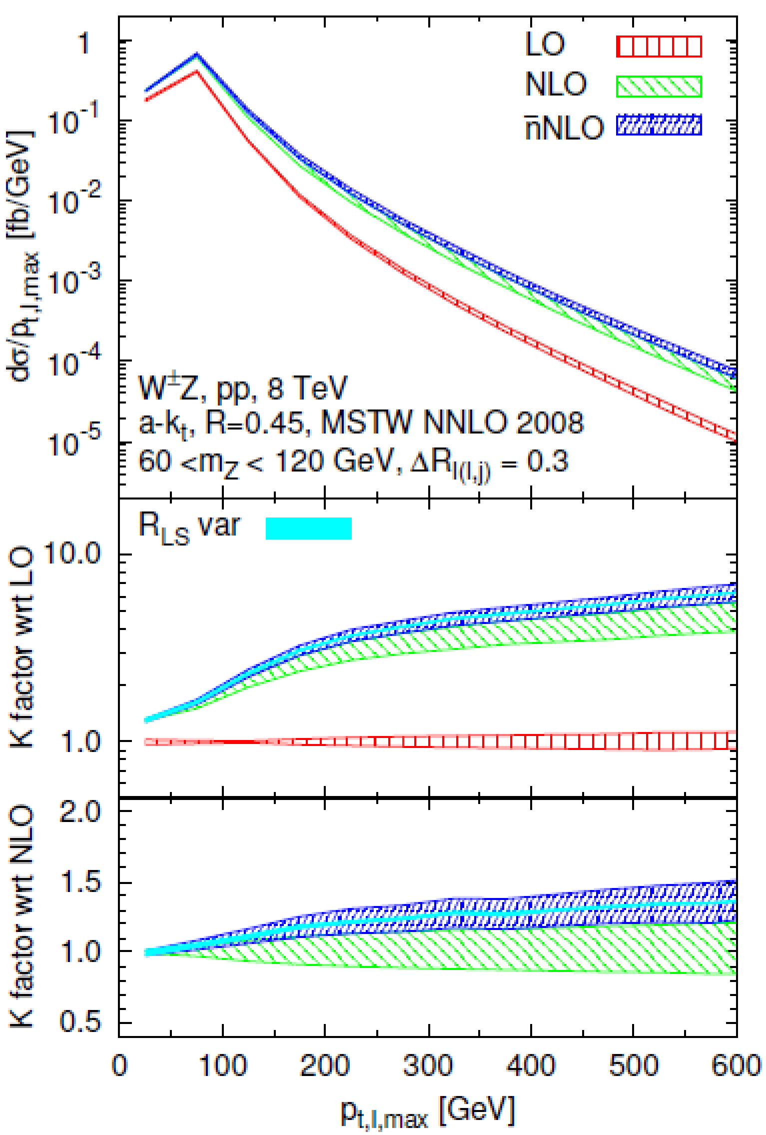

VBFNLO+LoopSim
LO
NLO
n̄NLO (μ)
n̄NLO (R_{LS})
box+Higgs
W+W-, pp, 8 TeV
with veto
a-kt, R=0.5, MSTW NNLO 2008
dσ/m_{ll} [fb/GeV]
K factor wrt LO
K factor wrt NLO
m_{ll} [GeV]

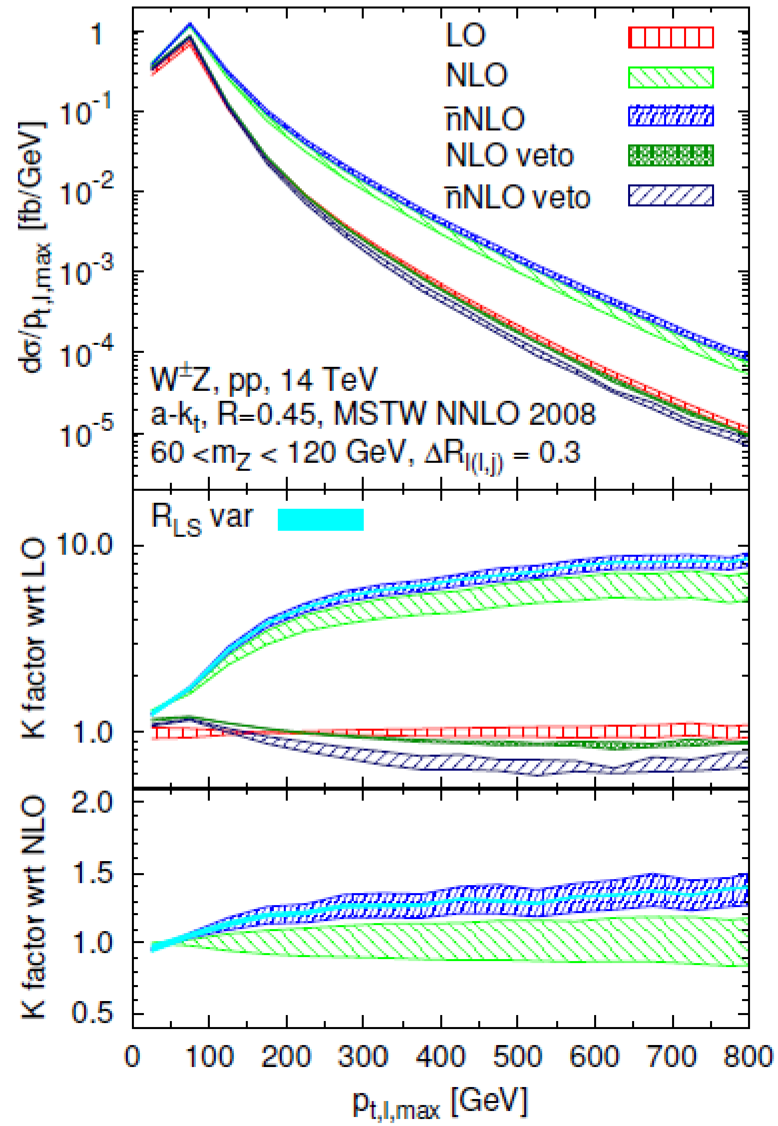
WZ



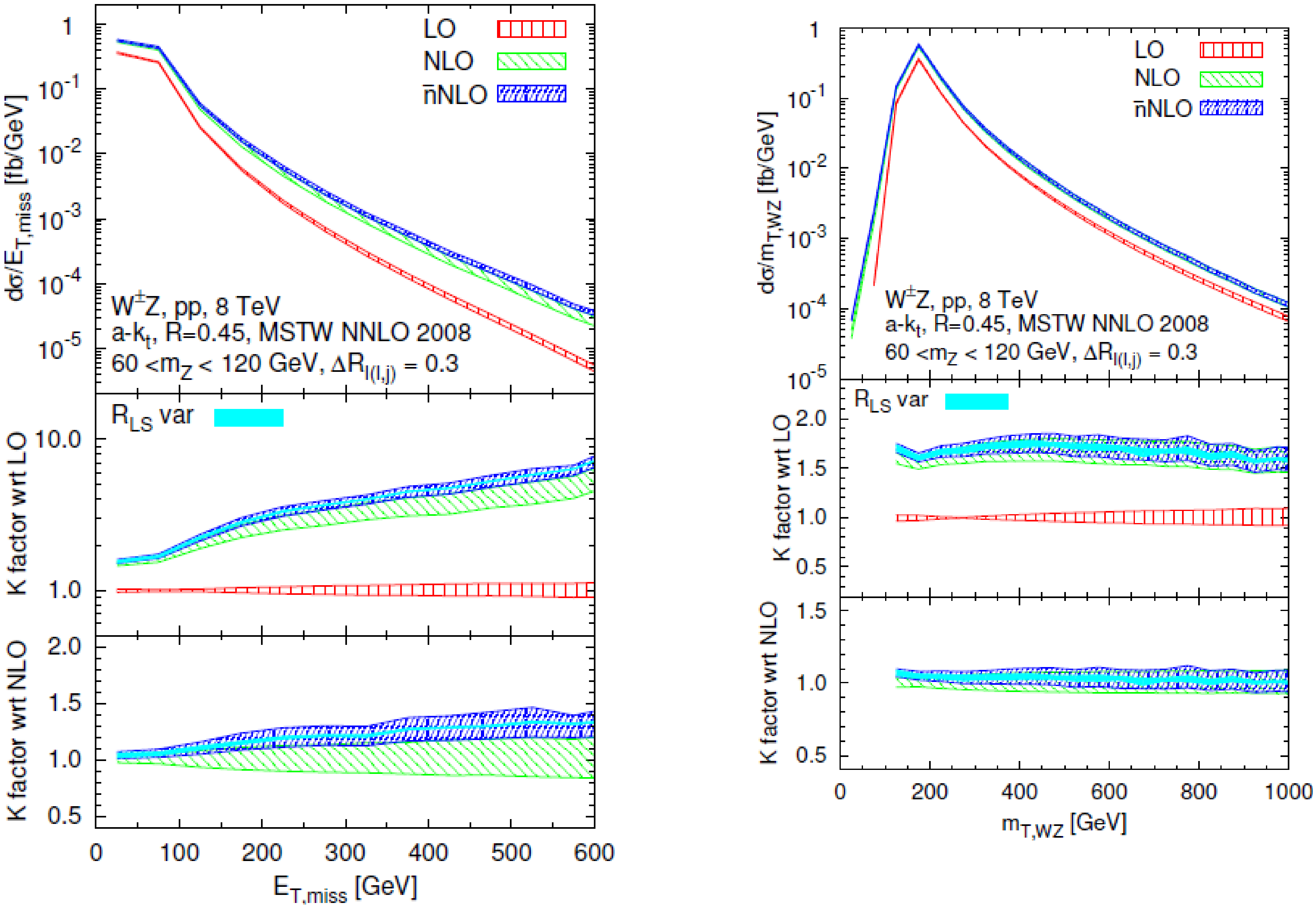
$$H_T = \sum p_{T,\text{jets}} + \sum P_{T,l} + E_{T,\text{mis}}$$

- Huge K-factors from LO to NLO
- Good agreement between $\bar{n}$LO and NLO at large H_T values
- Large $\bar{n}$NLO corrections
- Small R_{LS} uncertainties at large H_T
- Marginal reduction of scale uncertainties





- $\bar{n}$NLO corrections beyond scale uncertainty
- $\bar{n}$NLO with veto: Large corrections, larger scale uncertainties


LO
NLO
n̄NLO
$d\sigma/E_{T,miss}$ [fb/GeV]
$W^{\pm}Z$, pp, 8 TeV
a-k_t, R=0.45, MSTW NNLO 2008
60 <m_Z < 120 GeV, $\Delta R_{l(l,j)}$ = 0.3
R_{LS} var
K factor wrt LO
K factor wrt NLO
$E_{T,miss}$ [GeV]
$d\sigma/m_{T,WZ}$ [fb/GeV]
$m_{T,WZ}$ [GeV]