# ZZ Production at High Transverse Momenta Beyond NLO QCD

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in collaboration with Michael Rauch and Sebastian Sapeta

Based on

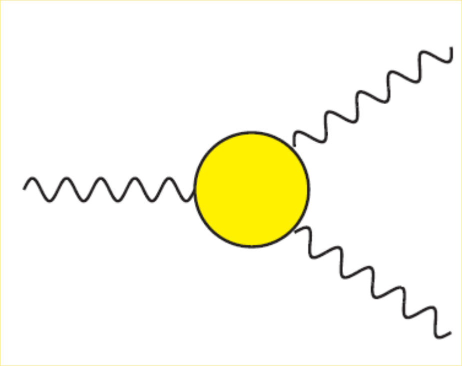
arXiv:1504.05588 [hep-ph]

# Contents

- Introduction
- Comparison with full NNLO results(Grazzini et al.)
- Differential distributions
  - Anomalous coupling searches
  - Higgs searches

# Di-boson production

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

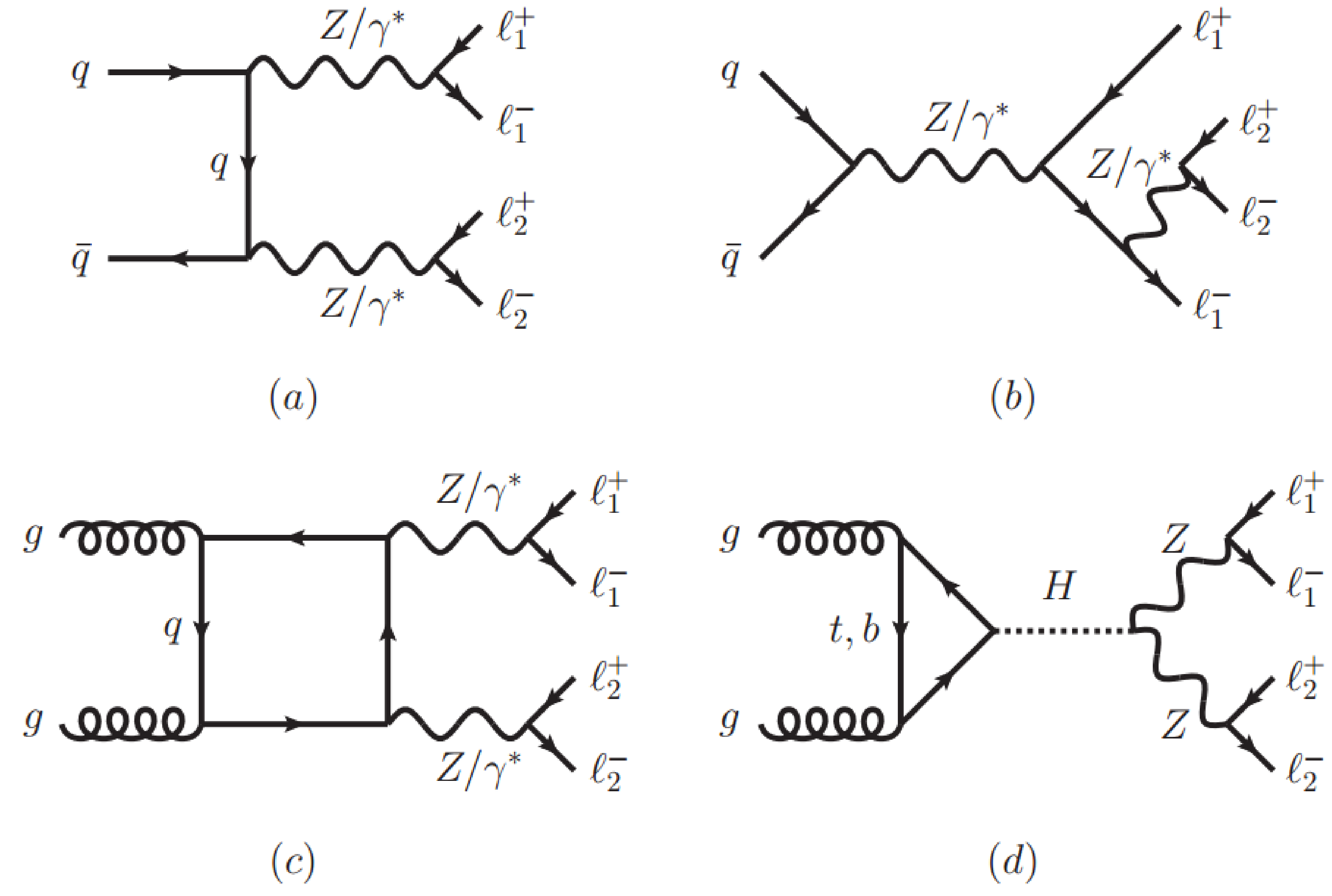


Status:

- NLO QCD known for a long time: 40-300%
- NLO EW known for some processes
- LO QCD GF induced contribution (NNLO) known: Up to20%
- Full NNLO QCD known for some processes:  40 %

Experimental Precision ⇒ Improve Theoretical

$$pp \to \ell_1^+ \ell_1^- \, \ell_2^+ \ell_2^- + X$$ **"ZZ"**




LO

GF LO

NNLO

# Beyond NLO QCD ?

NLO QCD corrections large

- New sub-processes
- New topologies

- At NNLO

  - New sub-processes
  - New topologies

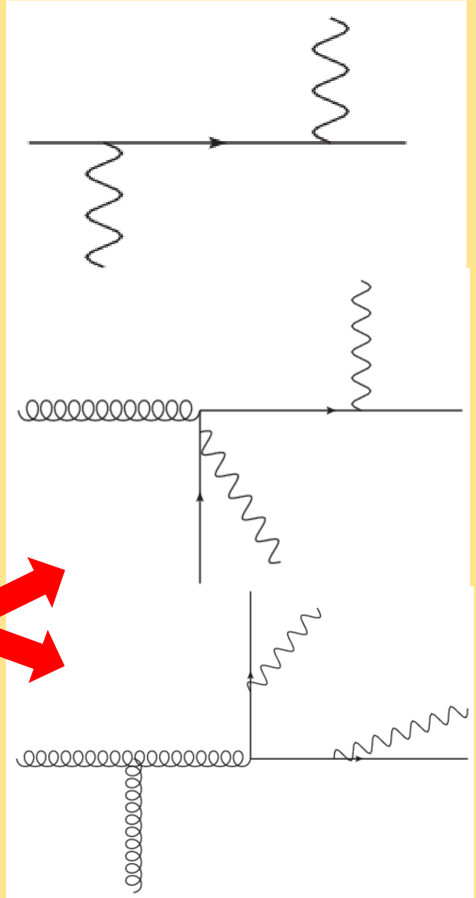
Potentially large corrections

LO

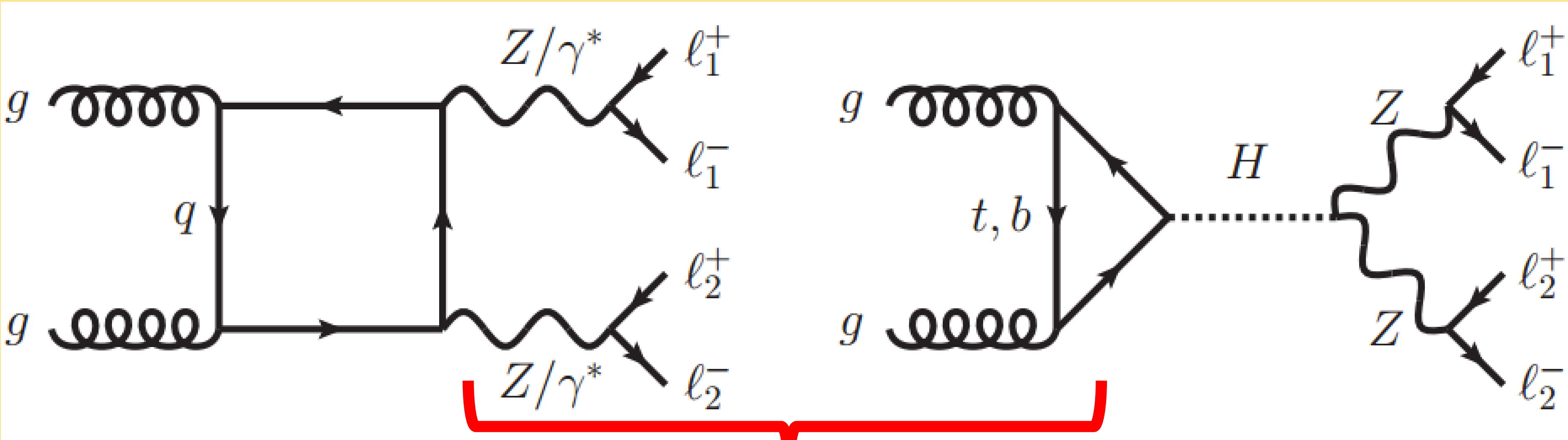
NLO

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

NNLO



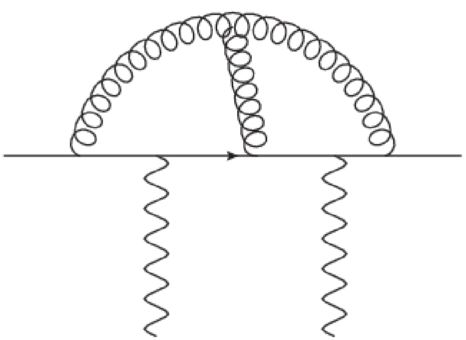
# ZZ at NNLO

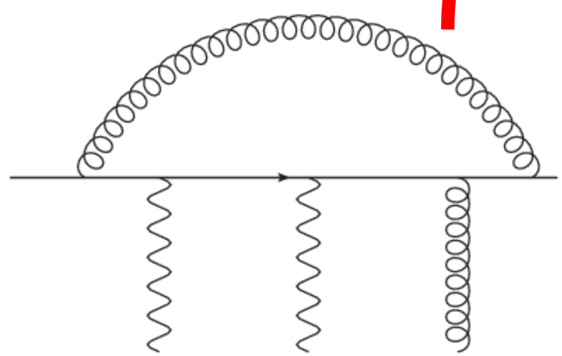


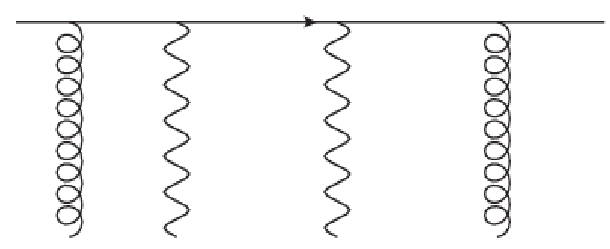

GF ZZ at LO

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

ZZj at NLO







# LoopSim

Program by: M.Rubin G.Salam and S.Sapeta: 1006.2144

Merge Samples of different multiplicty:

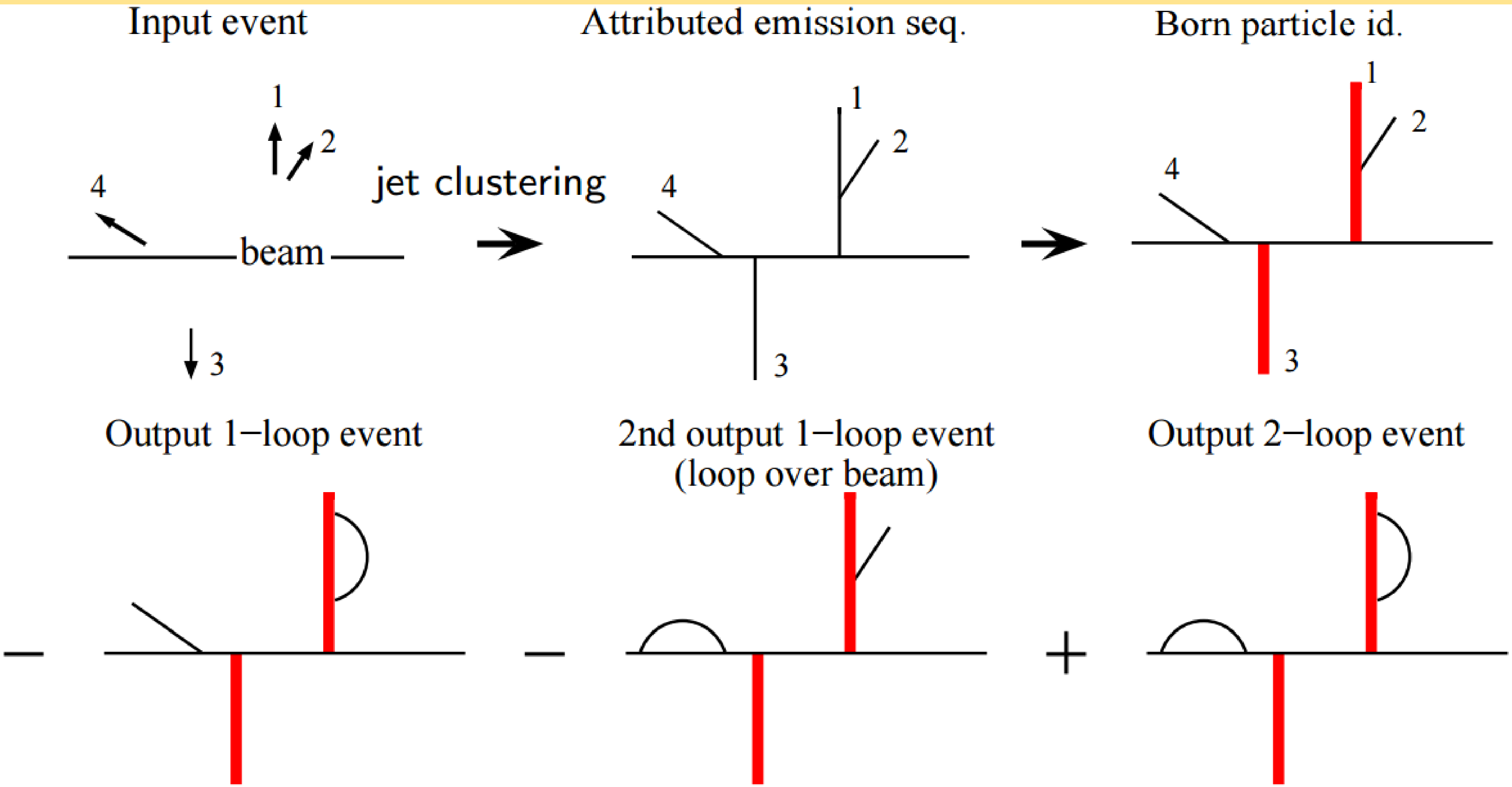
$$ZZ@LO + ZZj@LO \quad \rightarrow ZZ@\bar{n}\mathrm{LO} \qquad (GF)$$

$$ZZ@NLO + ZZj@NLO \rightarrow ZZ@\bar{n}\mathrm{NLO}$$

Simulates higher order corrections

Unitary approach: Cancellation of IR divergences

# 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

Exact at NNLO

# LHC at 8 TeV: Comparison

Ref.[32]: F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhfer, A. von Manteuffel, S. Pozzorini et al., Phys. Lett. B 735 (2014) 311 [arXiv:1405.2219]

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

GF 60% of total NNLO corrections

nNLO vs NNLO 2%: within scale uncertainties

# LHC at 8 TeV

## Input Parameters:

$$m_Z = 91.1876\,\text{GeV}\,, \qquad G_F = 1.16637 \times 10^{-5}\,\text{GeV}^{-2}$$

$$m_W = 80.398\,\text{GeV}\,, \qquad \alpha_{\text{em}}^{-1} = 132.3407\,,$$

$$m_H = 125\,\text{GeV}\,, \qquad \sin^2(\theta_W) = 0.22265\,,$$

$$\Gamma_Z = 2.508\,\text{GeV}\,, \qquad \Gamma_H = 0.004017\,\text{GeV}\,.$$

$$m_t = 172.4\,\text{GeV}\,, \qquad m_b = 4.855\,\text{GeV}\,.$$

## Scale:

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

## PDF set:

MSTW2008 at NNLO

# SM and AC Searches

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

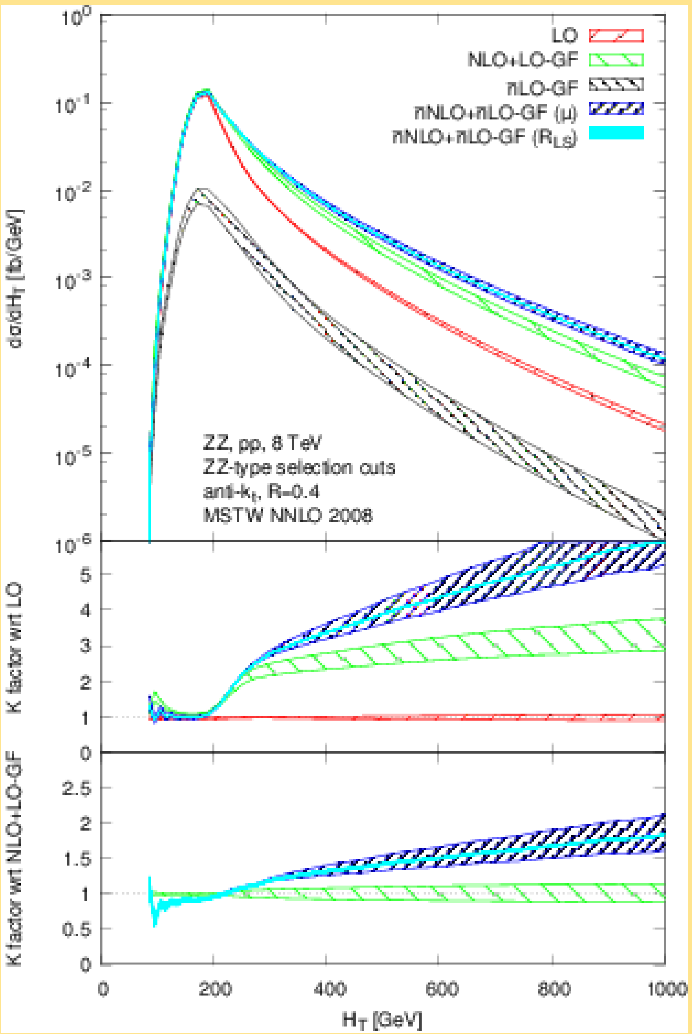
$ZZ$ selection: $m_{Z_1}, m_{Z_2} \in (66, 116)\,\text{GeV}\,,$

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

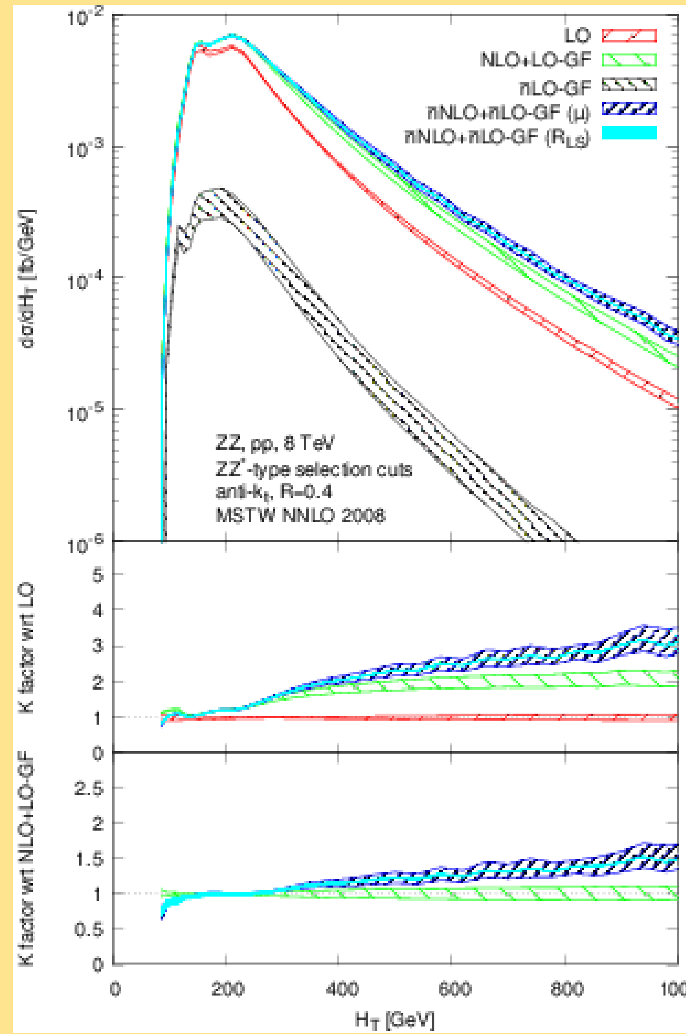
| | $ZZ$ | $ZZ^*$ |
|---|---|---|
| $\sigma_{\text{LO}}$ [fb] | $9.394(9)\ ^{+2.2\%}_{-3.1\%}$ | $1.0134(16)\ ^{+1.2\%}_{-1.9\%}$ |
| $\sigma_{\text{NLO}}$ [fb] | $12.057(19)\ ^{+1.6\%}_{-1.0\%}$ | $1.314(3)\ ^{+2.0\%}_{-1.5\%}$ |
| $\sigma_{\text{NLO+LO-GF}}$ [fb] | $12.929(19)\ ^{+3.4\%}_{-2.4\%}$ | $1.365(3)\ ^{+3.0\%}_{-2.2\%}$ |
| $\sigma_{\bar{n}\text{NLO}}$ [fb] | $13.15(8)\ ^{+3.3\%}_{-2.3\%}\ (\mu)\ ^{+0.8\%}_{-0.6\%}\ (R_{LS})$ | $1.417(12)\ ^{+2.0\%}_{-1.4\%}\ (\mu)\ ^{+0.8\%}_{-0.7\%}\ (R_{LS})$ |
| $\sigma_{\bar{n}\text{NLO}+\bar{n}\text{LO-GF}}$ [fb] | $13.15(8)\ ^{+3.3\%}_{-2.3\%}\ (\mu)\ ^{+0.9\%}_{-0.7\%}\ (R_{LS})$ | $1.427(12)\ ^{+2.3\%}_{-1.6\%}\ (\mu)\ ^{+0.9\%}_{-0.7\%}\ (R_{LS})$ |

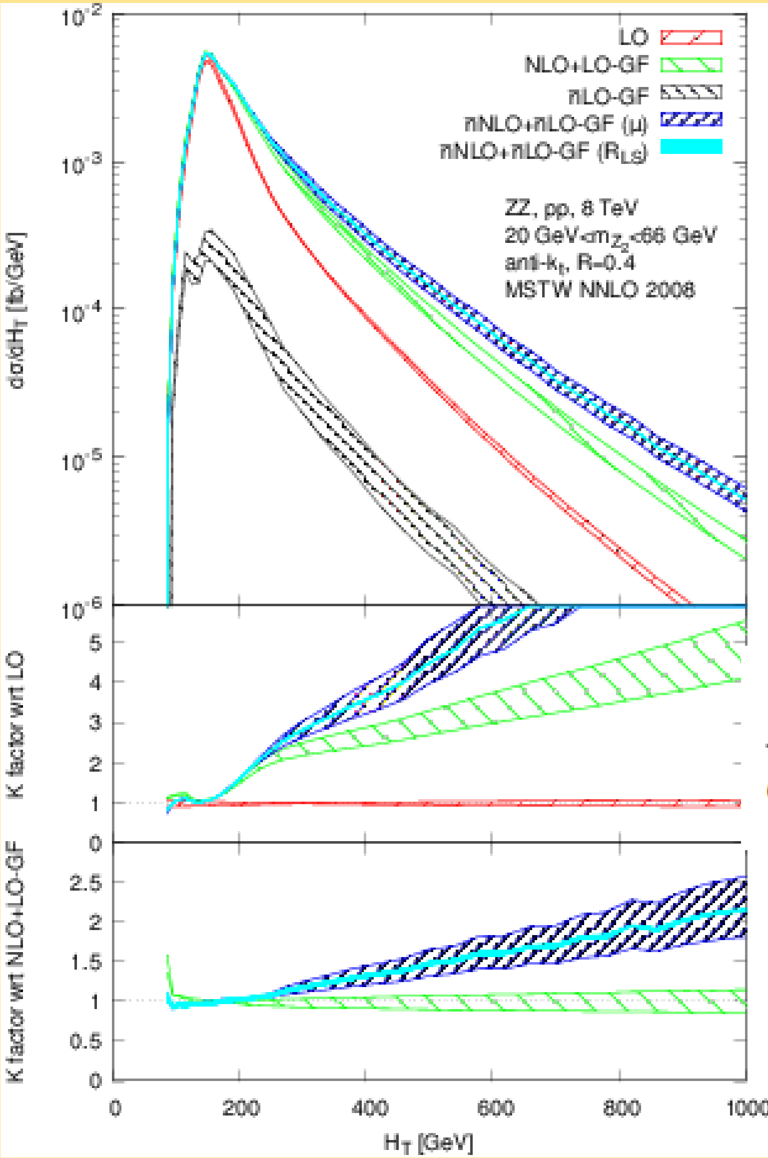
# $H_T$ Distributions

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

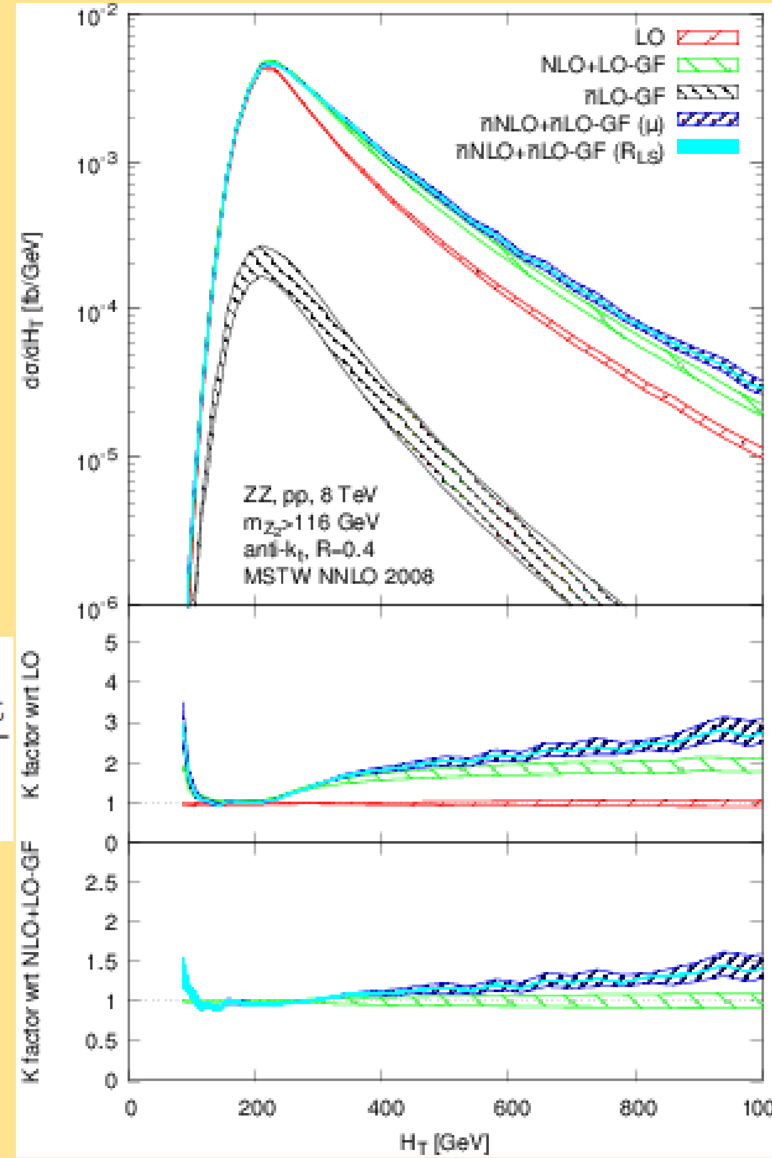



$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\,\text{jet}}^2}{m_Z^2}$$





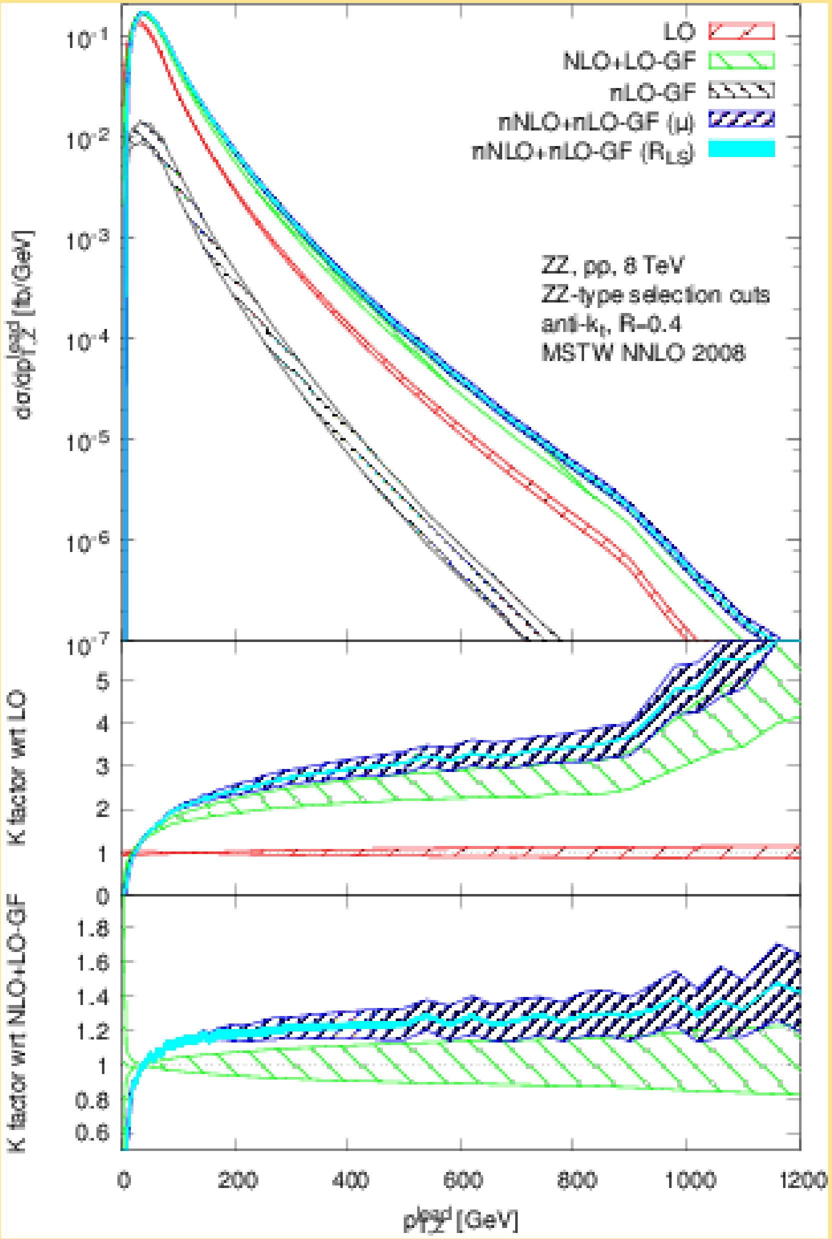

$$\frac{d\sigma}{d\Omega} \propto \ln \frac{p_{T,\,\mathrm{jet}}^2}{m_Z^2}$$




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

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

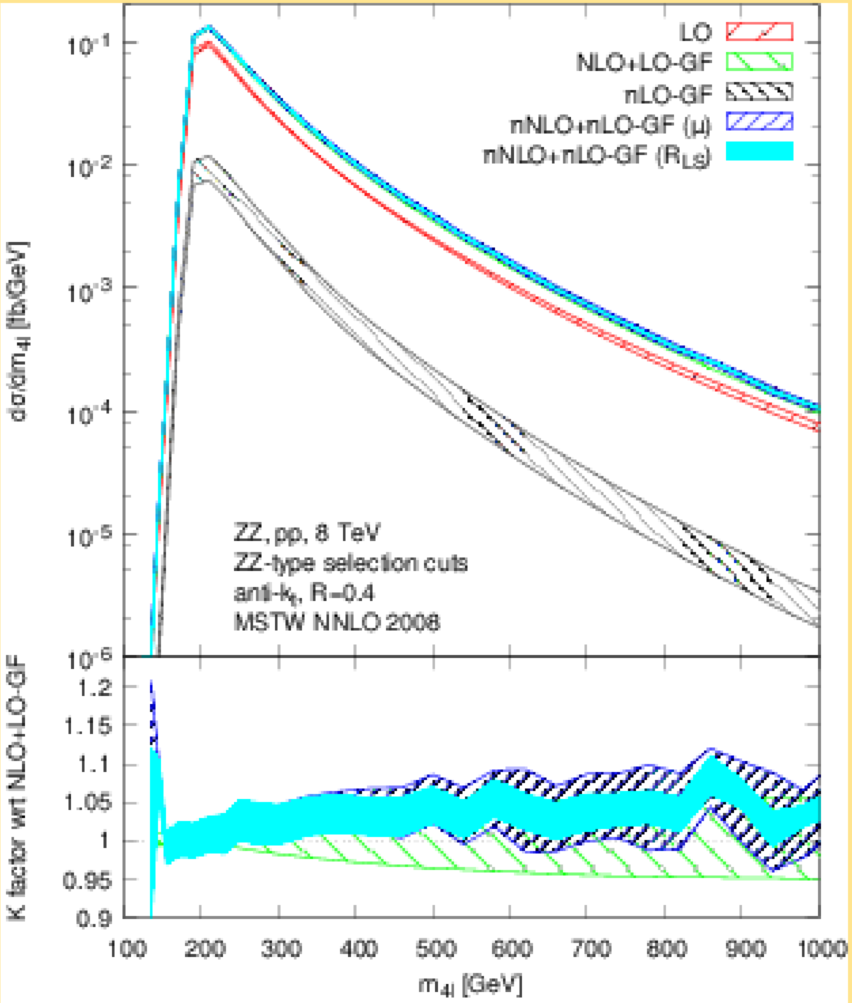
# $P_T$ Distributions

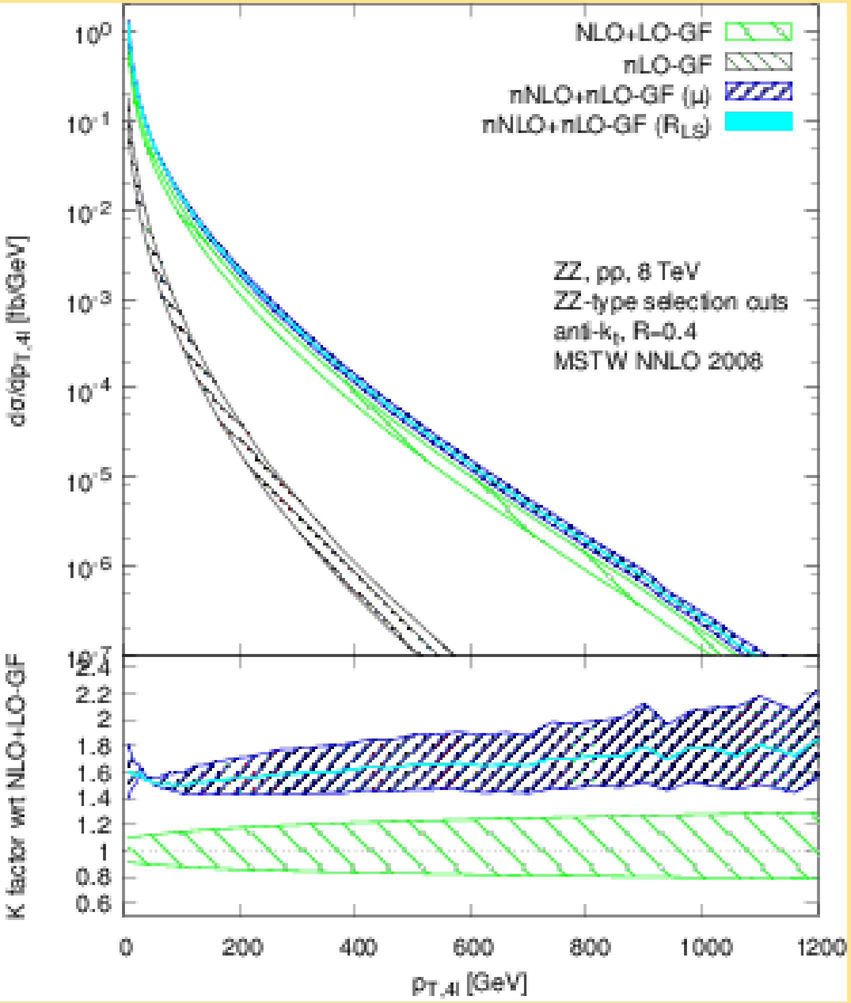



$$m_{\ell\ell}^2 \simeq \frac{1}{4} p_{T,Z}^2 \Delta R_{\ell,\ell}^2$$

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

# 4 lepton observables



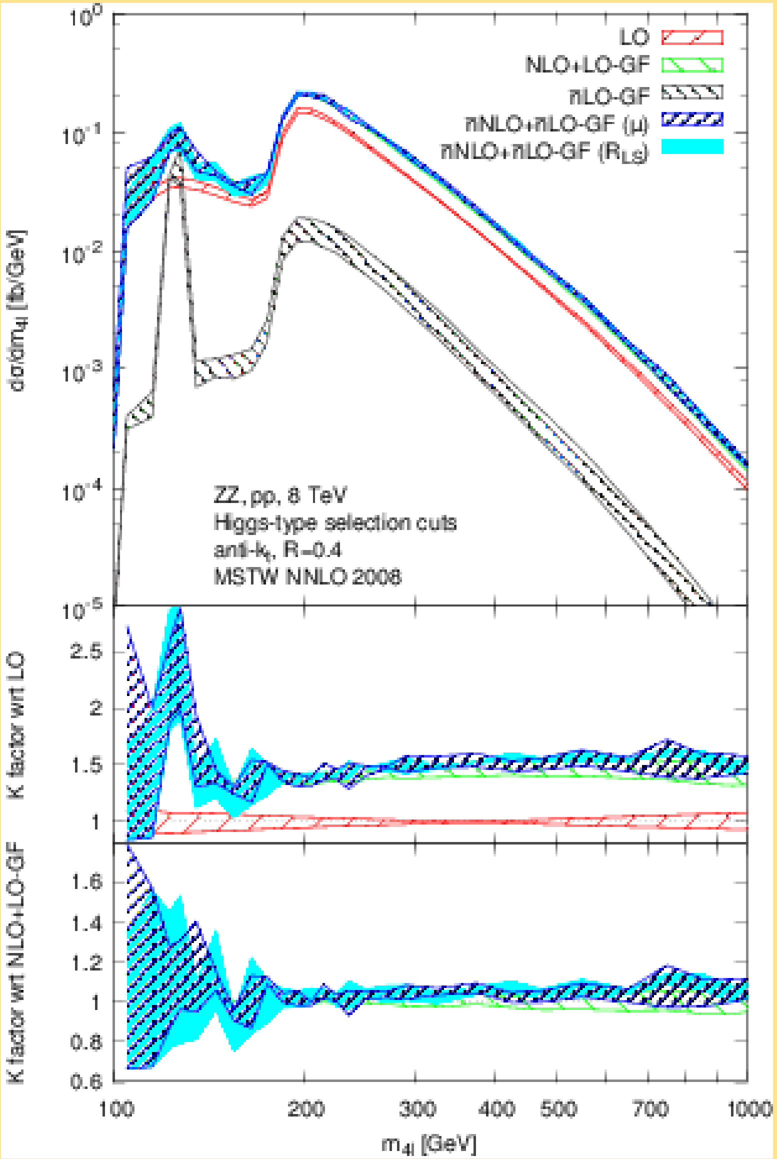



# Higgs Cuts

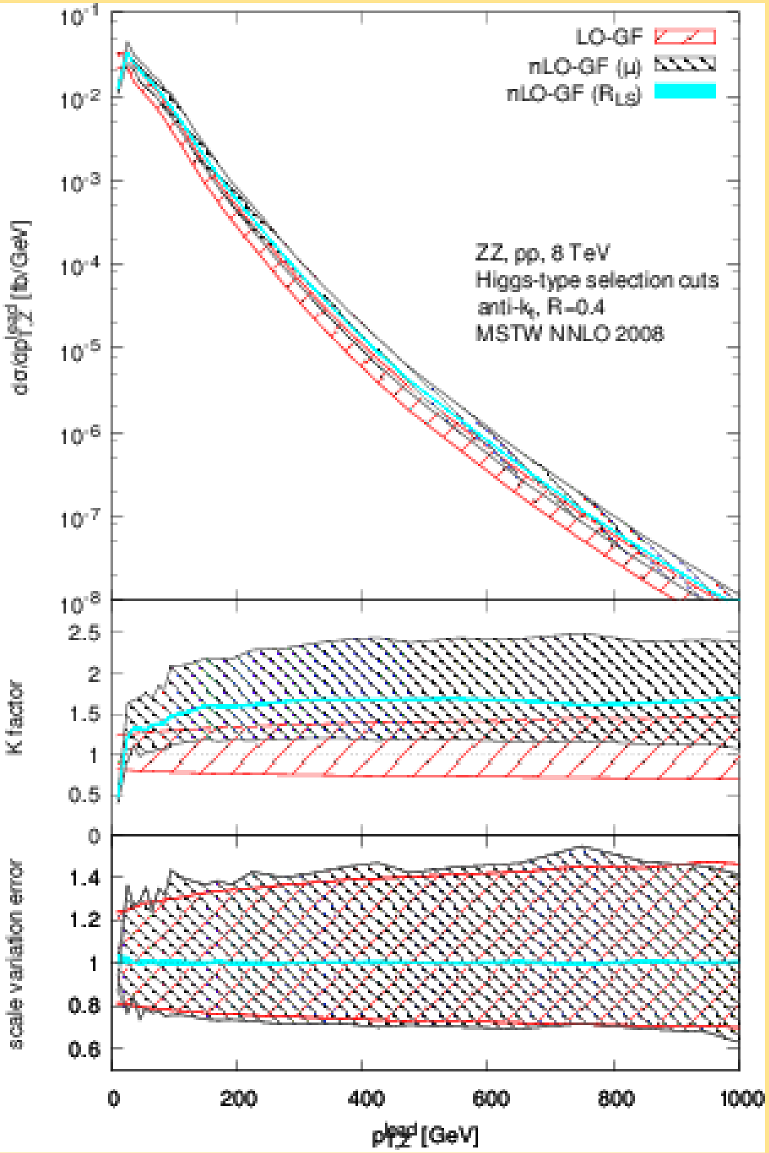
$$p_{t,e} > 7\,\text{GeV}\,, \qquad |\eta_e| < 2.5\,,$$
$$p_{t,\mu} > 5\,\text{GeV}\,, \qquad |\eta_\mu| < 2.4\,,$$
$$p_{t,\ell_{\text{hardest}}} > 20\,\text{GeV}\,, \qquad m_{4\ell} > 100\,\text{GeV}\,,$$
$$p_{t,\ell_{\text{second-hardest}}} > 10\,\text{GeV}\,,$$

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

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



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
dσ/dp_T,Z^lead [fb/GeV]
K factor
scale variation error
p_T,Z^lead [GeV]

# Summary

ZZ@nNLO + GF ZZj@LO

Total Cross section:

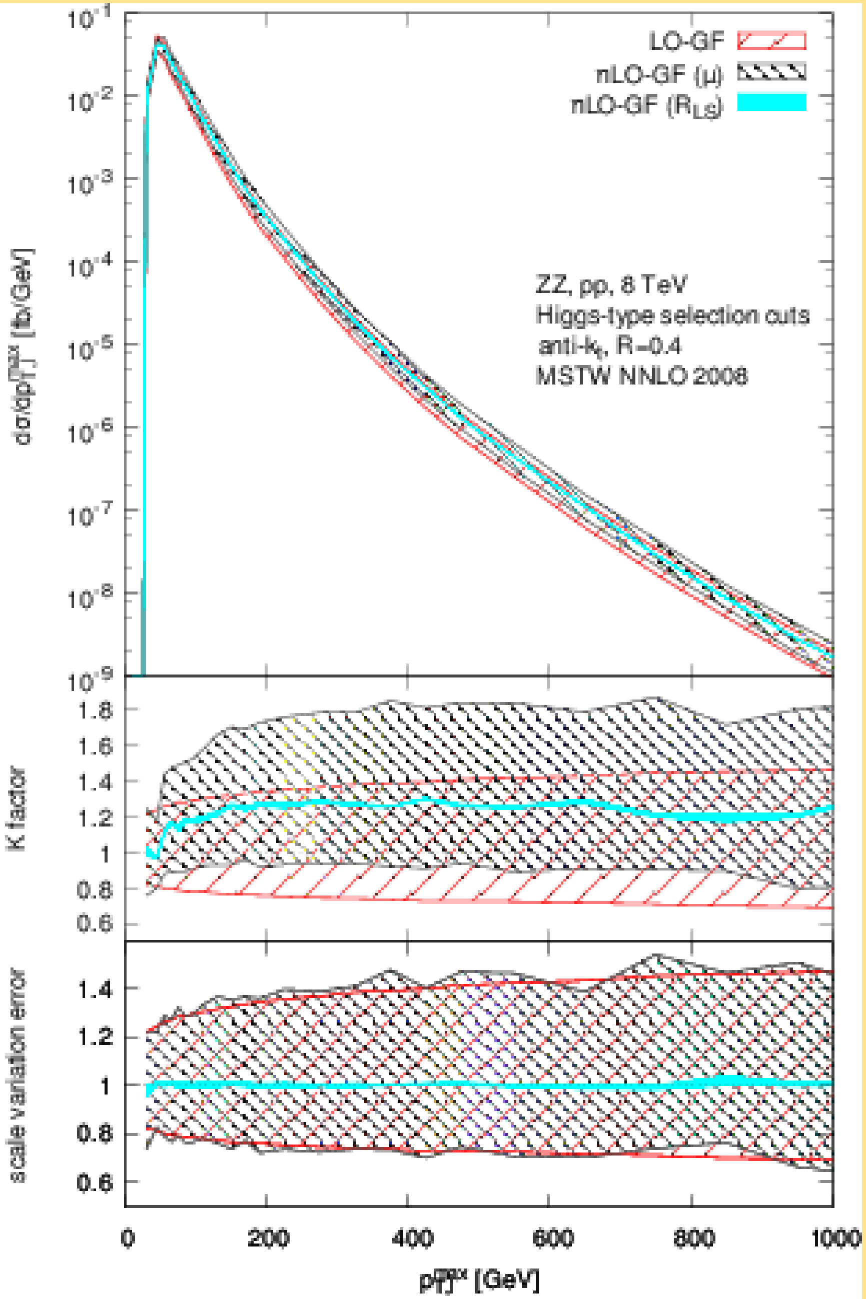
- Good agreement with known NNLO

Differential Distributions

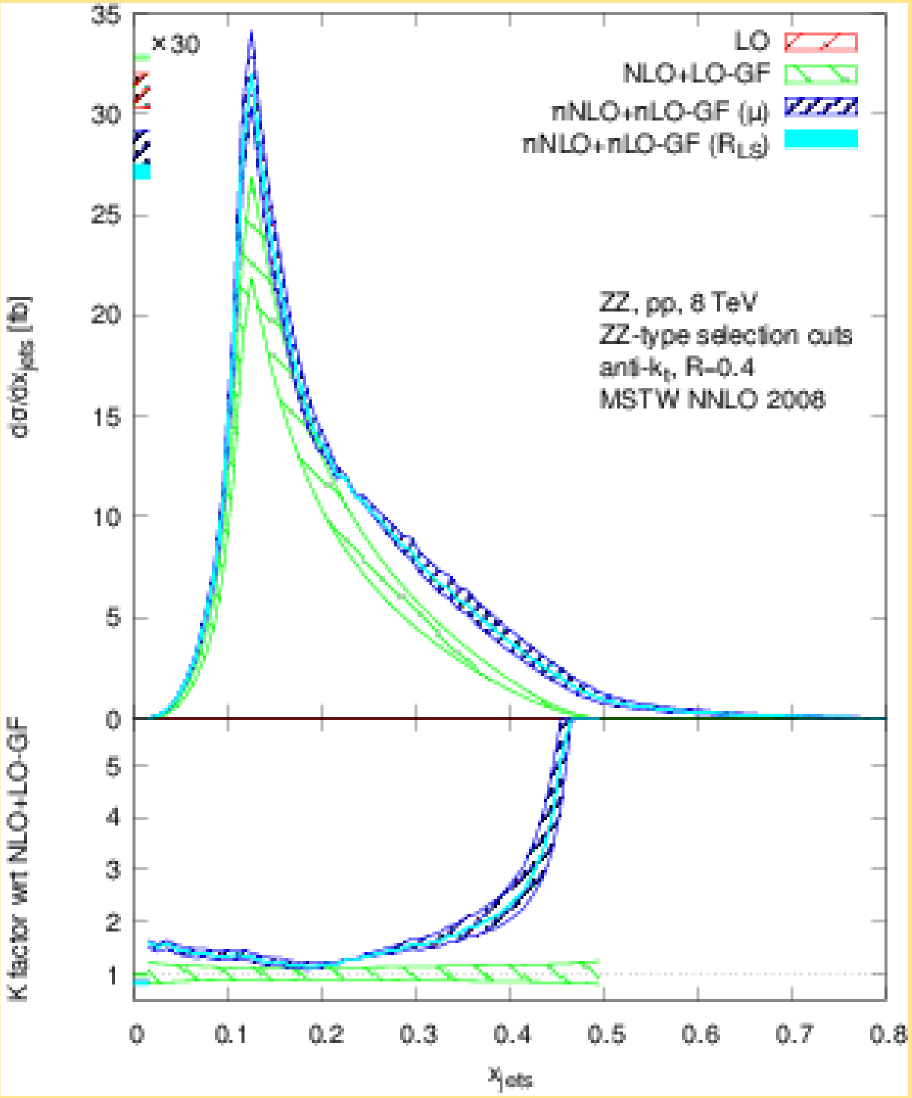
- Corrections can be large 30-100%
- Observable favoring LO kinematics:5%

Needed for accurate phenomenology

THANK YOU FOR YOUR ATTENTION



LO-GF
nLO-GF (μ)
nLO-GF ($R_{LS}$)
ZZ, pp, 8 TeV
Higgs-type selection cuts
anti-$k_t$, R=0.4
MSTW NNLO 2008
$d\sigma/dp_{T,J}^{max}$ [fb/GeV]
K factor
scale variation error
$p_{T,J}^{max}$ [GeV]




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