IFIC
INSTITUT DE FÍSICA CORPUSCULAR

MARIE CURIE ACTIONS

Precision Multiboson Phenomenology

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THEORY DIVISION

Table of Contents

Multi-Boson Production at LHC

- SM background for BSM searches
- Background to Higgs searches
- Access to triple and quartic electroweak couplings

Process ($V \in \{Z, W, \gamma\}$)	Relevant for
0. $pp \to VV$	H, new physics
1. $pp \to VV+$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t}+$ 2 jet	$t\bar{t}H$
4. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$,new physics
5. $pp \to VV+$ 2 jets	VBF $\to H \to VV$
6. $pp \to V+$ 3 jets	new physic signatures
7. $pp \to VVV$	SUSY trilepton

Diboson Production Channels

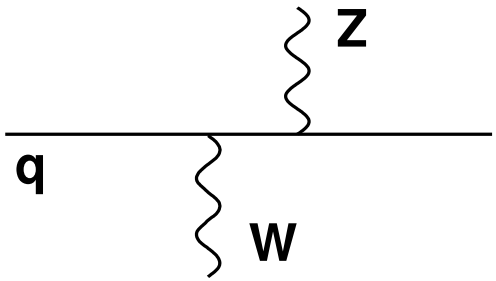
Where do we stand from the theoretical side?

- NLO QCD known for a long time: 40-300% [VBFNLO,MCFM]
- NLO EW known for some processes
- NNLO QCD GF induced contribution known: Up to 20%
- Full NNLO QCD for $\gamma\gamma$: $\sim$ 40 % [S. Catani et al. PRL 108 (2012) 072001]
- Two loop Virtuals $W\gamma, Z\gamma$: [T.Gehrmann, L.Tancredi, JHEP 1202 (2012) 004]
- Two loop Virtuals WW: [G.Chachamis in pre, PoS RADCOR2009 (2010) 059]

Experimental Precision $\rightarrow$NNLO?

WZ Topologies

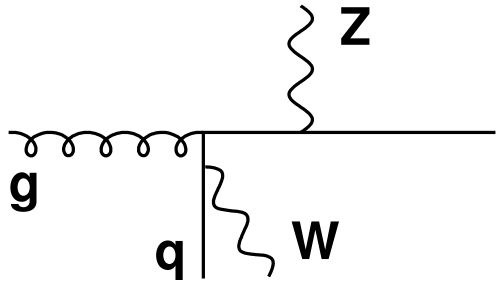
LO



α_{EW}^2

- Back-to-Back topologies

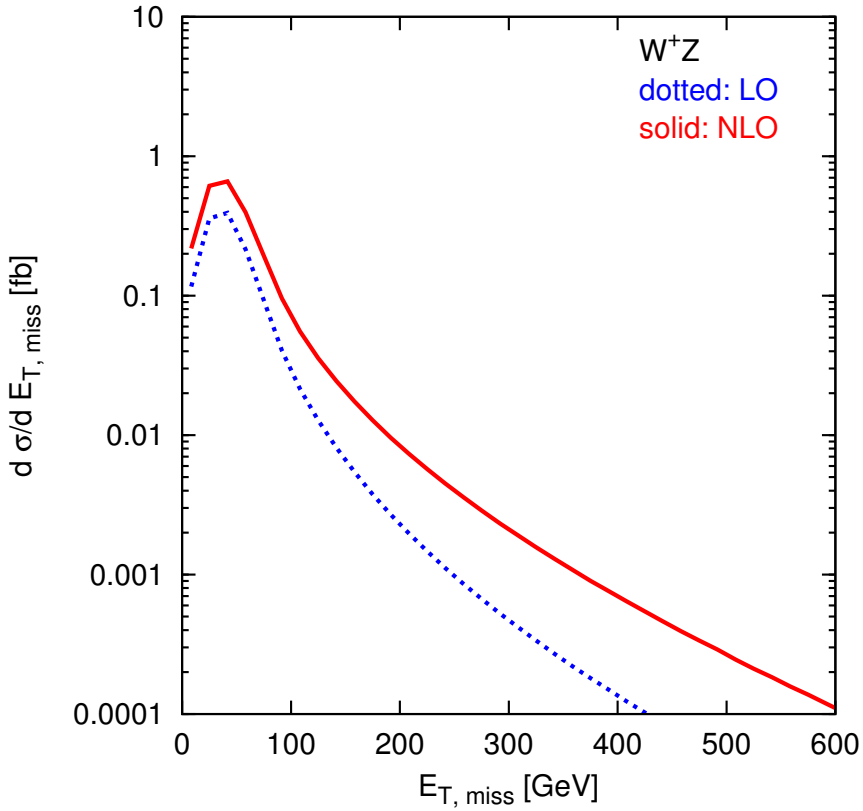
NLO QCD (WZ+j at LO)

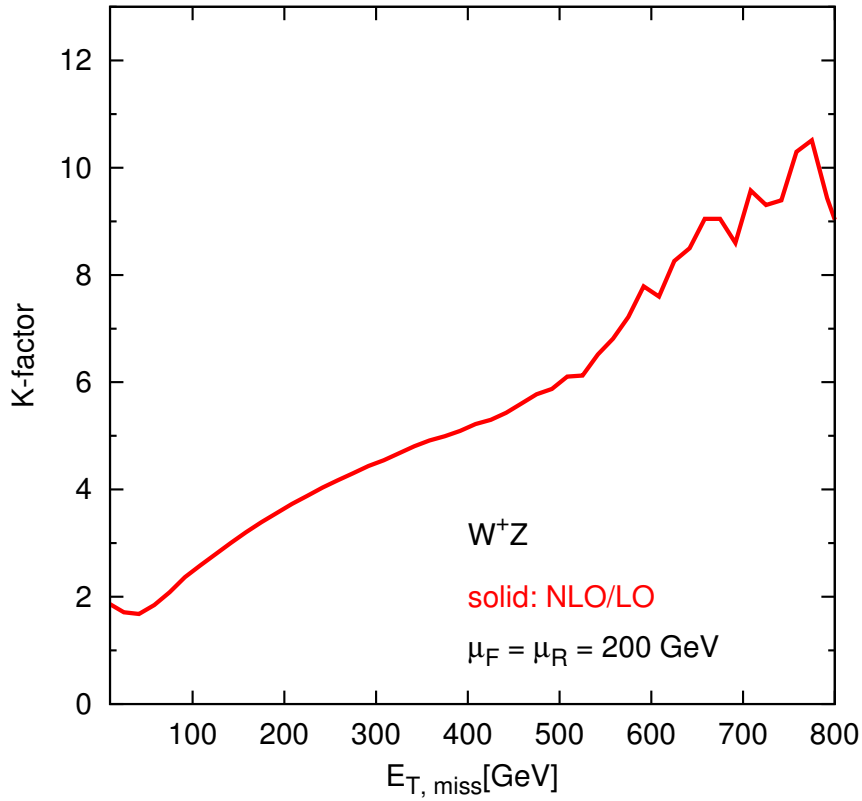


- New Channels: Gluons in initial state: LO
- New Topologies: Soft and collinear emissions

$$\alpha_{EW}^2 \, \alpha_s \, \ln^2 \frac{p_T}{M_W}$$

NLO QCD correction[VBFNLO: J.Bellm]

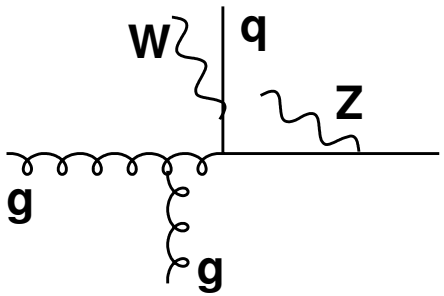




Dominated by new topologies, WZj events AT LO $\rightarrow$ NNLO ?

WZj@NLO: Towards WZ@NNLO

- Real Corrections to WZ@NNLO



$$\alpha_{EW}^2 \, \alpha_s^2 \, \ln^2 \frac{p_T}{M_W} \, \ln^2 \frac{p_T}{M_z}$$

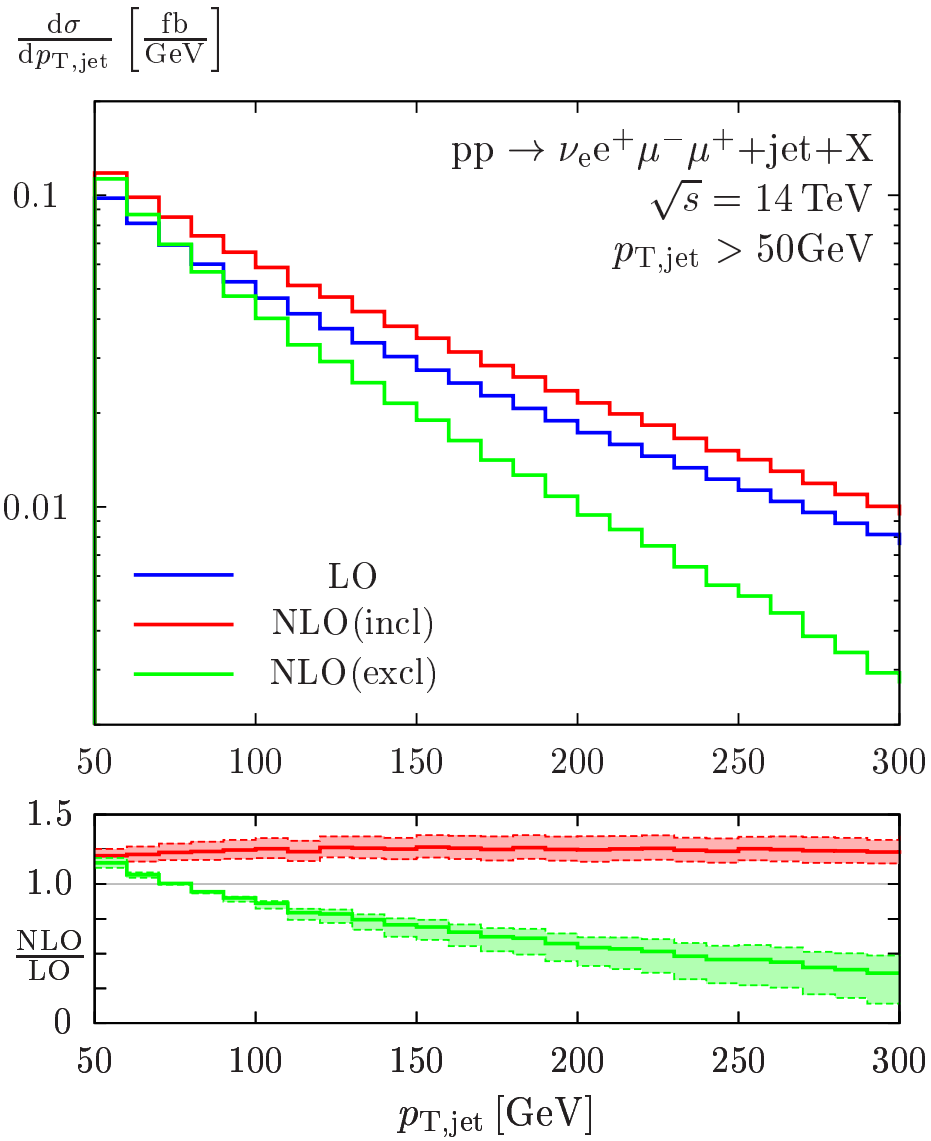
  - New Channels: Gluons in initial state at LO
  - New Topologies: Soft and collinear emissions

- Virtual $\times$ Real corrections to WZ@NNLO

Missing:

- Virtual α_s^2 corrections
  - No new topologies $\rightarrow$ Naturally Supressed

WZj@NLO: FC,C.Englert,S.Kallweit,M.Spannowsky,D.Zeppenfeld:1006.0390



- K-factor ~ 1.4
  - $\rightarrow$ Potential large NNLO corrections to WZ
    - WZ@NLO includes WZj at LO
  - Scale uncertainty: 10%
  - Vetoed sample badly modelled
- Similar conclusions for $VV + j$
- Anomalous Couplings:

  FC,C.Englert,M.Spannowsky:1006.3090

WZ beyond NLO QCD: FC,S.Sapeta:1209.4595

VBFNLO: WZ@NLO and WZj@NLO
LoopSim: M.Rubin G.Salam and S.Sapeta: 1006.2144

Merge samples of different multiplicity

WZ@LO + WZj@LO $\rightarrow$ WZ@$\bar{n}$LO

WZ@NLO + WZj@NLO $\rightarrow$ WZ@$\bar{n}$NLO

- Simulates higher loop corrections $\rightarrow$

cancel IR singularities in a consistent way

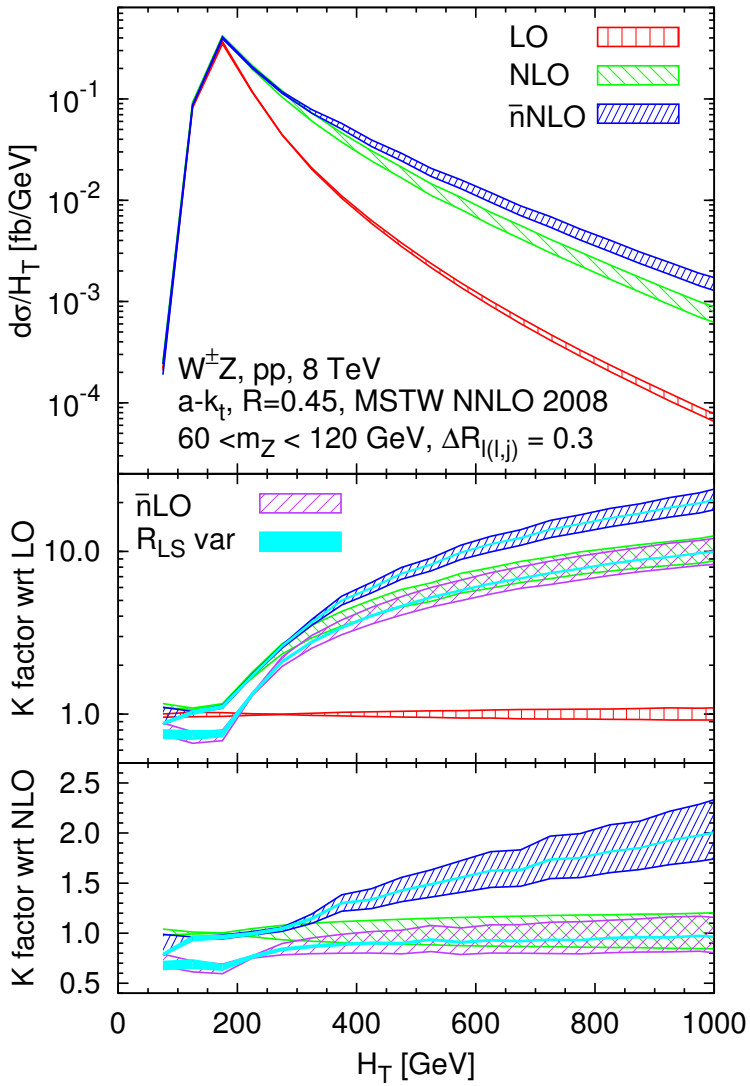
$$\sigma^{(A)}_{\bar{n}\text{NLO}} - \sigma^{(A)}_{\text{NNLO}} = \mathcal{O}\left(\alpha_s^2 \sigma^{(A)}_{\text{LO}}\right)$$

Calculational details:

- 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:

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

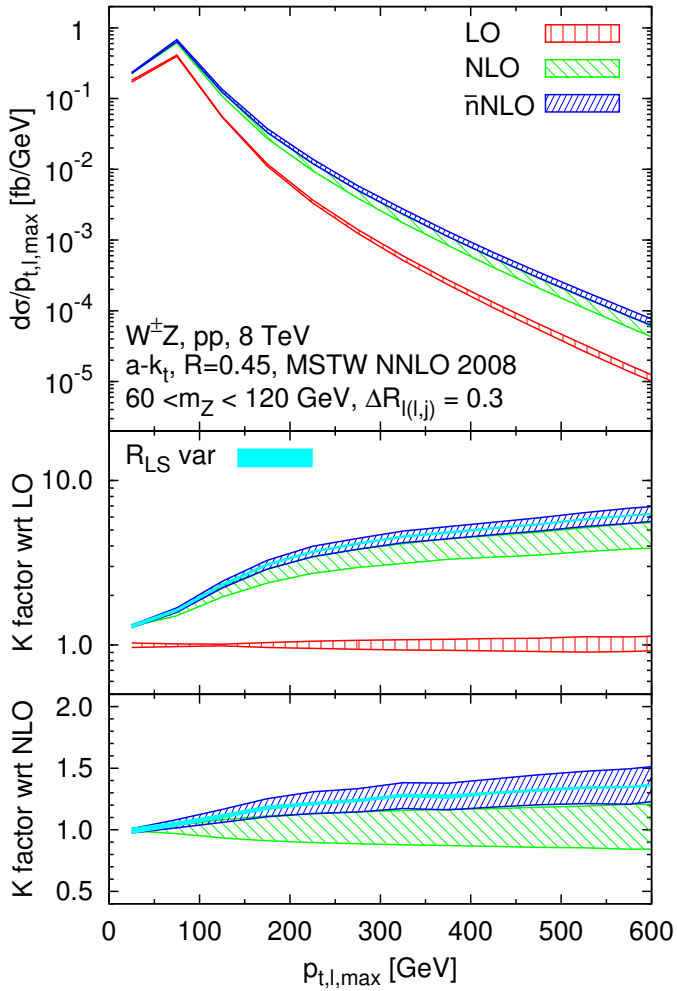
H_T: Validation and more

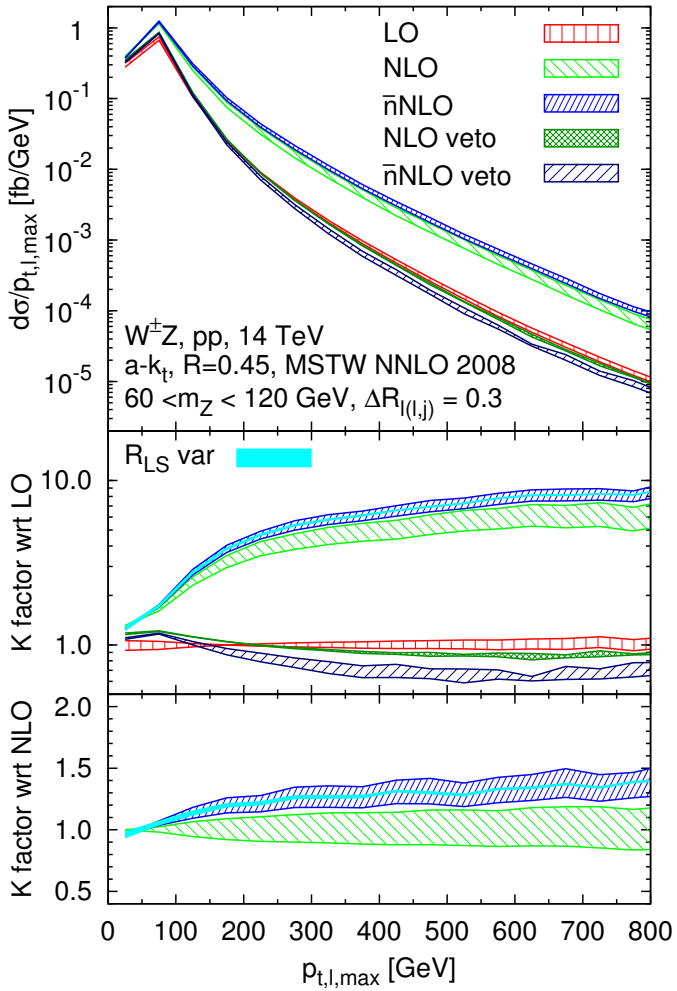


$$H_T = \sum p_{T,\text{jets}} + \sum P_{T,l} + E_{T,\text{mis}}$$

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

P_T of the hardest lepton





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

Tri-boson Production:

Reach phenomenology:

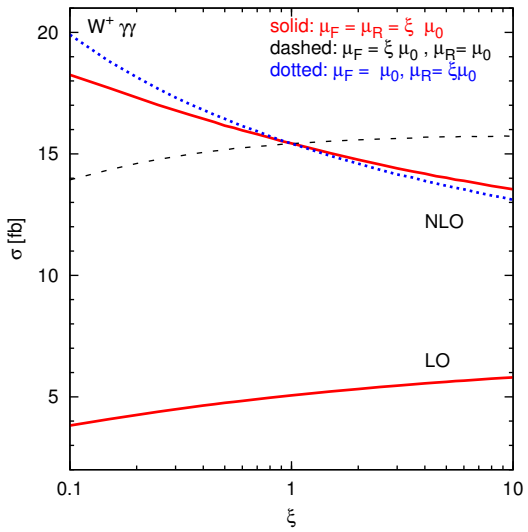
- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature
- Background to Higgs searches (e.g. $WH \to W\gamma\gamma$)
- Possibility to obtain information about triple and quartic electroweak couplings

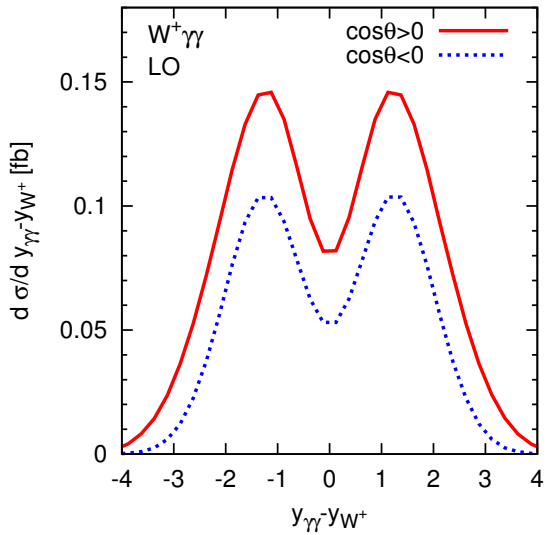
All channels at NLO QCD:

VBFNLO
http://www.itp.kit.edu/∼vbfnloweb/wiki/doku.php

$W^{\pm}\gamma\gamma$ at NLO: G.Bozzi, FC, M.Rauch, D.Zeppenfeld:1103.4313

- Background to new physics (LSP gravitino)





- K-factor=NLO/LO $\approx$ 3.3!
- $K_{VVV} \approx 1.4 - 2$
- $W\gamma\gamma + j$ at LO dominates overall scale uncertainty

$W^{\pm}\gamma\gamma$ at NLO: G.Bozzi, FC, M.Rauch, D.Zeppenfeld:1103.4313

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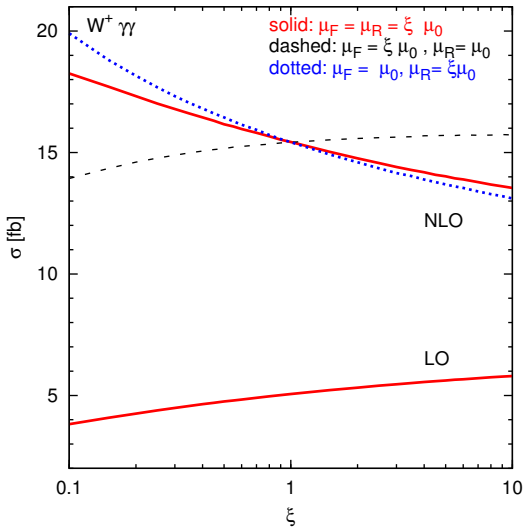

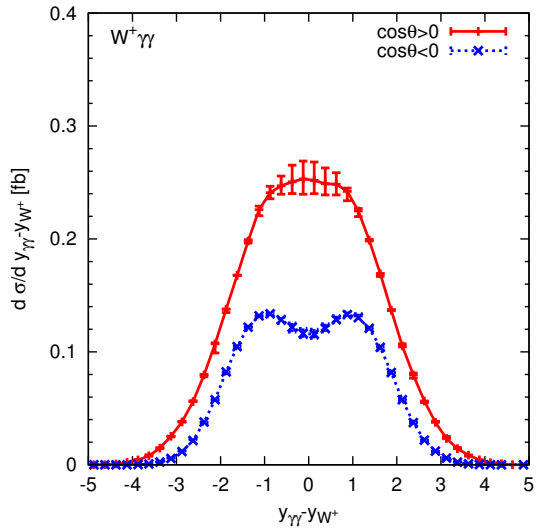

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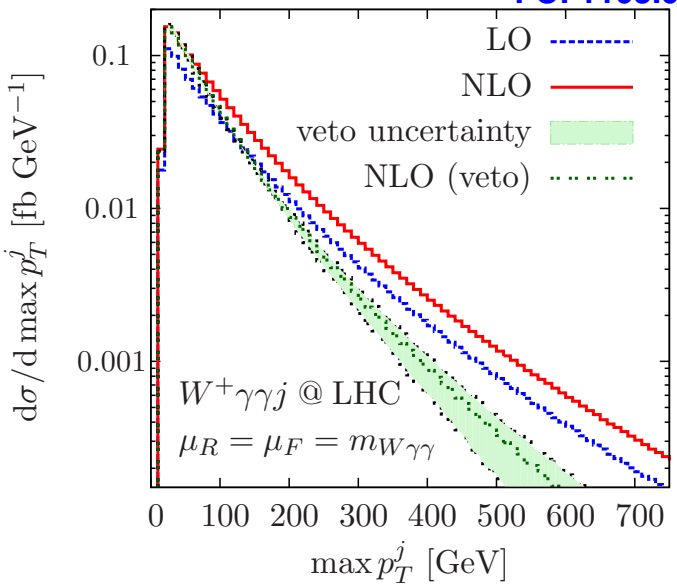
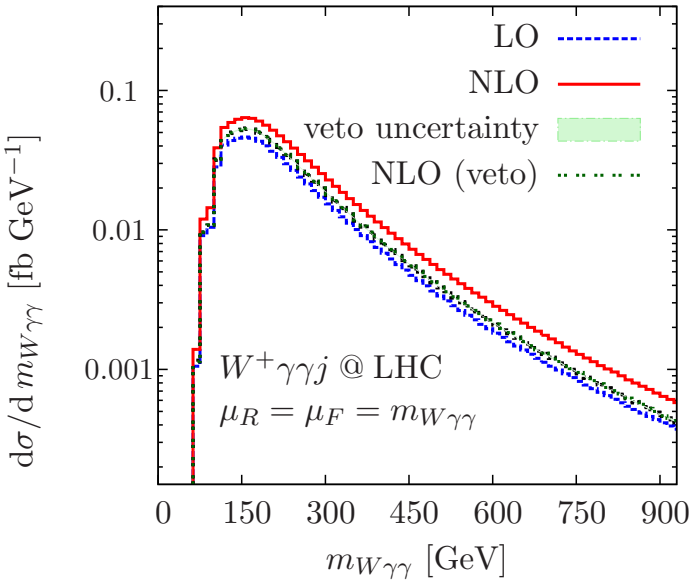
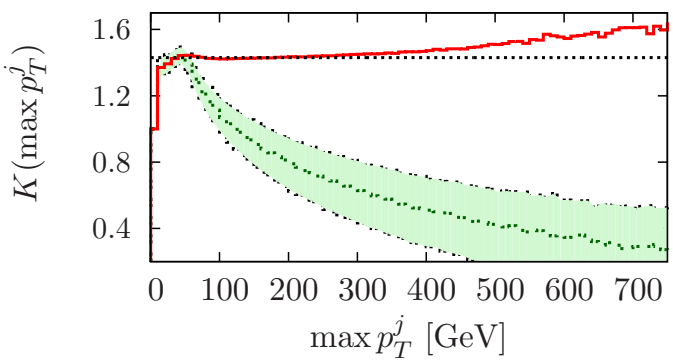
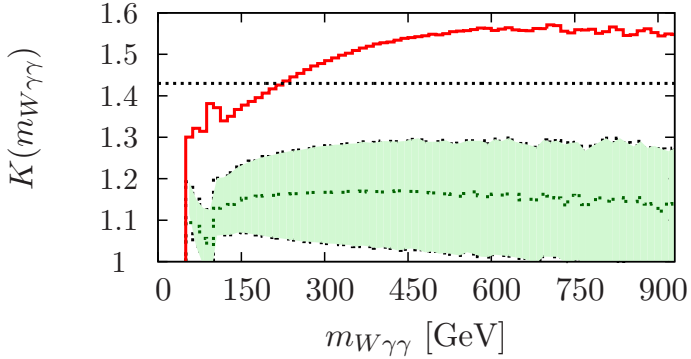
$W^{\pm}\gamma\gamma + j$ at NLO: FC,C.Englert,M.Rauch,D.Zeppenfeld:1106.4009

FC: 1105.0920









- Vetoed badly modelled!
- Additional jet radiation affects LO kinematics

Summary:

- NLO QCD corrections are large: $30-40\%$ for VVj, $40-100\%$ for $VV(V)$, for $V\gamma\gamma$ 300%
- Scale dependence uncertainty is significantly improved
- Strong phase space dependence

$\rightarrow$ Devoted and flexible MonteCarlo program: VBFNLO

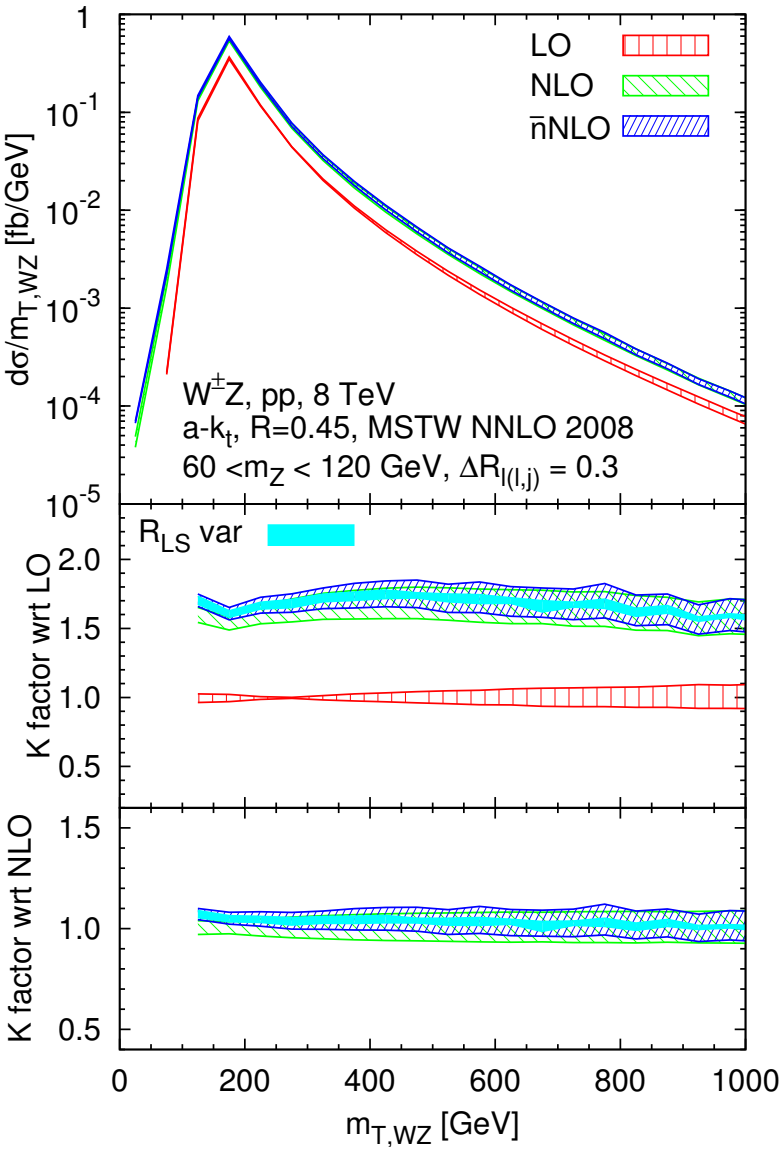
Beyond NLO:

- $\bar{n}$LO vs NLO: LoopSim work well
- $\bar{n}$NLO corrections can be large
  - for high p_T observables
  - H_T: 100 %, $p_{T,Z(W)}$: 30%

Next:

- Anomalous couplings, other processes($WW, WA \ldots$)

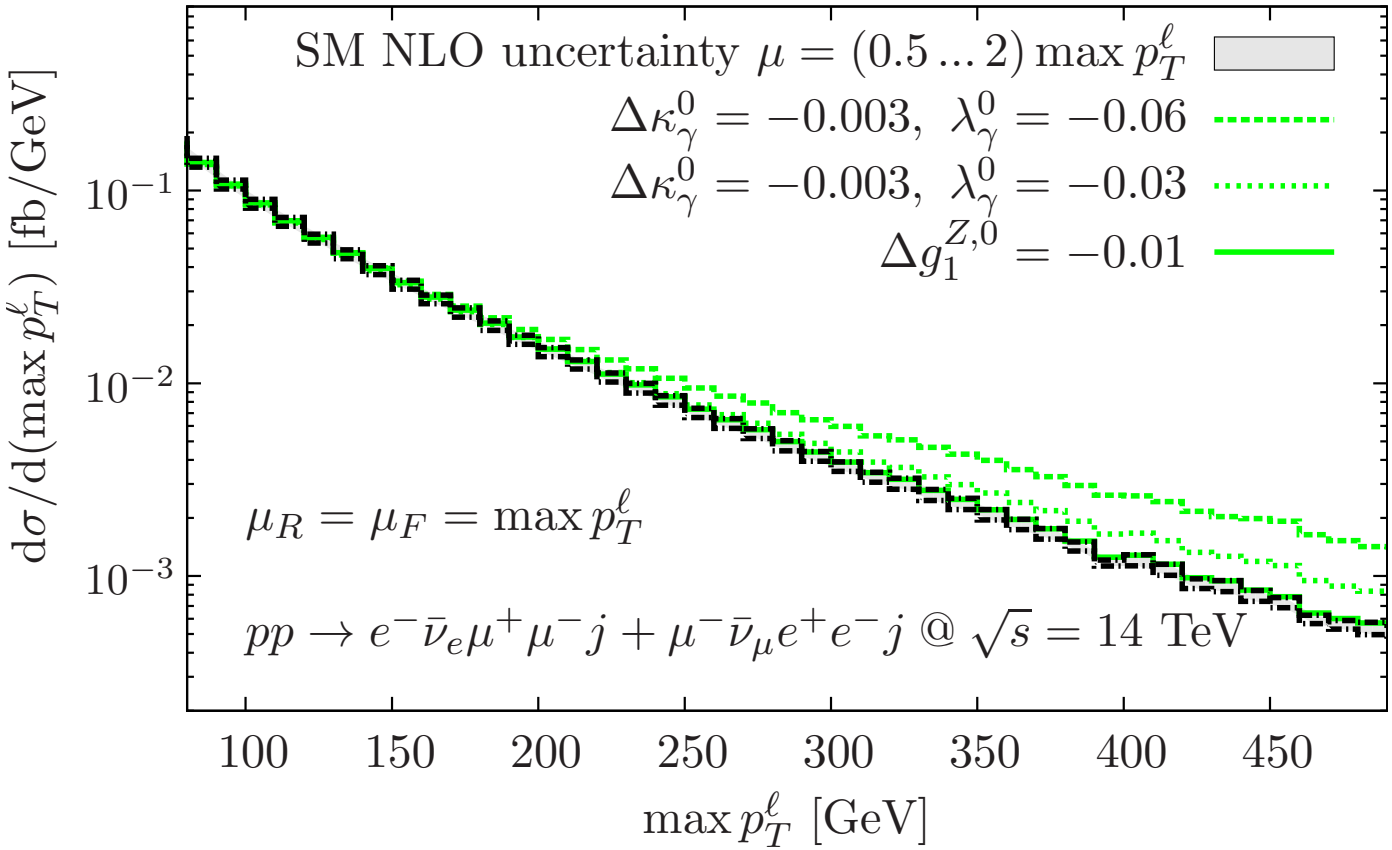
$M_{T,WZ}$



$$m_{T,WZ} = (E_T^W + E_T^Z)^2 - (p_x^W + p_z^z)^2 - (p_y^W + p_y)^2$$

- LO Kinematics: back-to-back configurations $\rightarrow$ No large log$'$ s $\rightarrow$ $\bar{n}NLO$ corrections small
- finite loop effects visible$\rightarrow$ R_{LS} uncertainty

Anomalous Couplings: FC,C.Englert,M.Spannowsky:1006.3090



- Sensitivity at high p_T beyond scale uncertainties