SM VVV Production at LHC

Francisco Campanario | 30/09/2013

INSTITUTE FOR THEORETICAL PHYSICS

Table of Contents

VVV Production at LHC

- 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
- QCD corrections to $pp \to VVV + X$ on experimentalist's wishlist: [The QCD, EW, and Higgs Working group: hep-ph/0604120]

Process ($V \in \{Z, W, \gamma\}$	Relevant for
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	various new physics signatures
7. $pp \to VVV$	SUSY trilepton

Status of NLO QCD Corrections *VVV*

On-shell production:

- ZZZ without Higgs-contributions [Lazopoulos,Menikov,Petriello;hep-ph/0703273]
- $ZZZ, W^+W^-Z, W^+W^+W^-$ and W^+ZZ without Higgs-contributions [Binoth,Ossola,Papadopoulos,Pittau; arXiv:0804.0350]
- EW NLO for W^+W^-Z [D. T. Nhung, L. D. Ninh and M. M. Weber;arXiv:1307.7403[hep-ph]

In VBFNLO with leptonic decays:

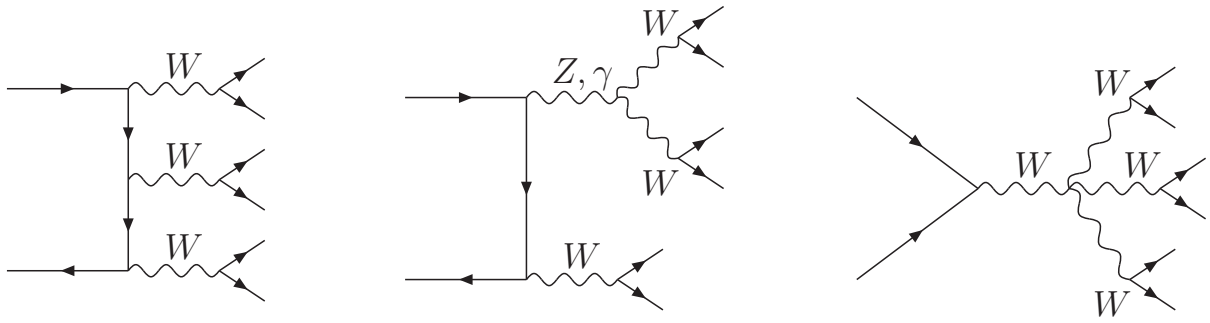
- W^+W^-Z, $W^\pm W^\mp W^\pm$ and $ZZW^\pm$ and Higgs graphs [Hankele,Zeppen-feld;arXiv:0712.3544; FC,Hankele,Oleari,Prestel,Zeppenfeld;arXiv:0809.0790]
- $W^+W^-\gamma$ and $ZZ\gamma$ [Bozzi,FC,Hankele,Zeppenfeld:arXiv:0911.0438]
- $W^\pm Z\gamma$ [Bozzi,FC,Rauch,Rzehak,Zeppenfeld:arXiv:1011.2206]
- $W^\pm\gamma\gamma$ [Baur, Wackeroth,Weber;arXiv:1001.2688] with leptonic decays [Bozzi,FC,Rauch,Zeppenfeld: Phys. Rev. D **83** (2011) 114035]
- $Z\gamma\gamma(\gamma\gamma\gamma)$ [Bozzi,FC,Rauch,Zeppenfeld: Phys. Rev. D **84** (2011) 074028]

$pp \to VVV$ in vbfnlo at NLO QCD

- $pp \to W^+W^-Z \to l_1^+\nu_1 l_2^-\bar{\nu}_2 l_3^- l_3^+$ (Higgs resonance+AC)
- $pp \to W^\pm W^\mp W^\pm \to l_1\nu_1 l_2\nu_2 l_3\nu_3$ (Higgs resonance+AC)
- $pp \to ZZW^\pm \to l_1^- l_1^+ l_2^- l_2^+ l_3\nu_3$ (Higgs resonance+AC)
- $pp \to ZZZ \to l_1^+ l_1^- l_2^- l_2^+ l_3^- l_3^+$
- $pp \to W^+W^-\gamma \to l_1^+\nu_1 l_2^-\bar{\nu}_2\gamma$
- $pp \to ZZ\gamma \to l_1^- l_1^+ l_2^- l_2^+\gamma$
- $pp \to W^\pm Z\gamma \to l_1\nu_1\gamma$
- $pp \to W^\pm\gamma\gamma \to l_1\nu_1\gamma\gamma$
- $pp \to Z\gamma\gamma \to l_1^- l_1^+\gamma\gamma \quad (\bar{\nu}\nu\gamma\gamma)$
- $pp \to \gamma\gamma\gamma$

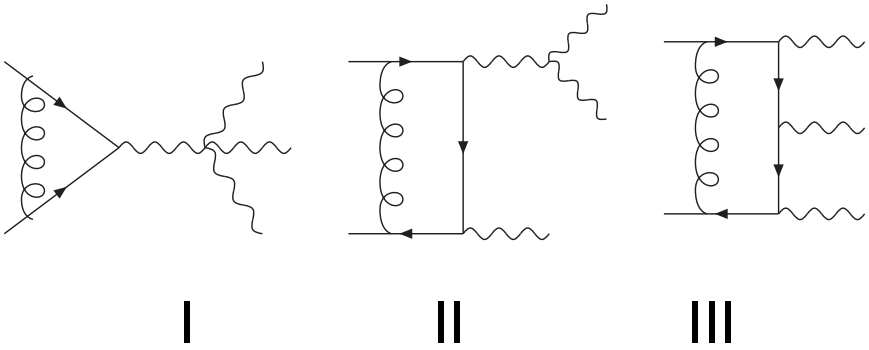
Photon isolation via Frixione criterion

$W^{\pm}W^{\pm}W^{\mp}$ Production



- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contributions included
- Interference terms due to indentical particles in the final state have been neglected (0.1% effect)
- All fermion mass effects neglected($H\tau\tau$-coupling=0): 1% effect

Virtual and Real Corrections

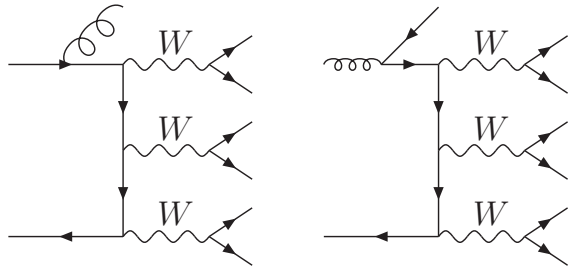


I II III

I Vertex corrections propor -tional to Born amplitude

II 4-point functions

III Up to 5-point functions (Pentagons)



- Final and initial state gluons
- Hundred of Feynman-graphs
- Soft and collinear singularities subtracted with Catani-Seymour prescription

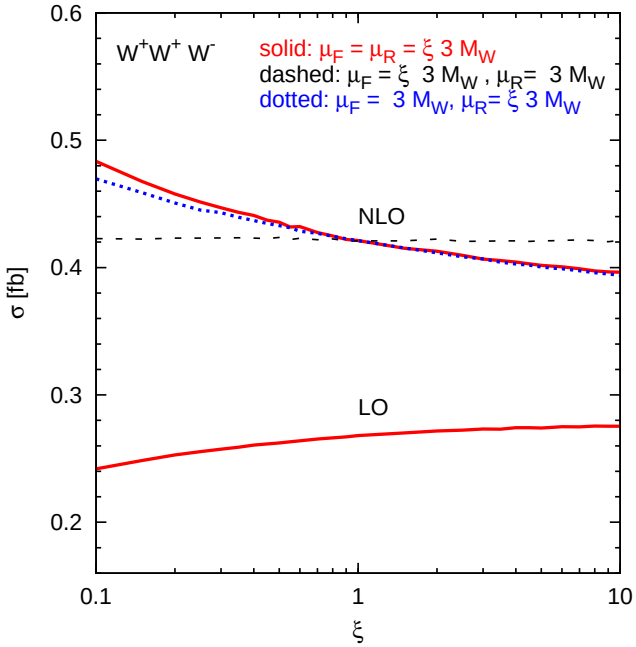
Loop Integrals: [FC:1105.0920]

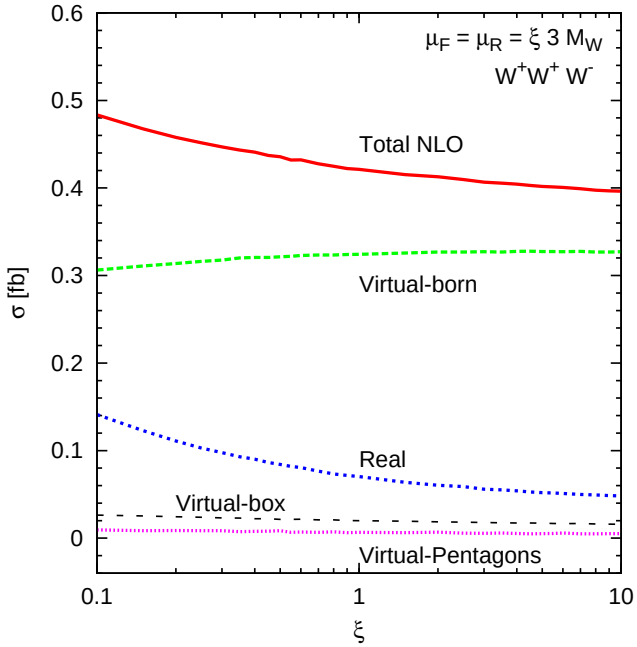
$W^+W^+W^-$ Production

- PDFs: CTEQ6L1 at LO and CTE10, $\alpha_s(m_z)$ at NLO
- Cuts and Masses:

$$p_{T_{l(\gamma)}} > 20(20)\ \mathrm{GeV} \qquad |y_{l(\gamma)}| < 2.5 \qquad R_{l\gamma(j)} > 0.4 \qquad R_{j\gamma} > 0.7$$
$$m_H = 126 GeV, \qquad M_W = 80.398 GeV, \qquad M_Z = 91.1876 GeV$$
$$\sin\theta_W = 0.22264, \qquad \alpha^{-1} = 1/132.3407$$
$$G_F = 1.16637 \cdot 10^{-5} GeV^{-2}$$

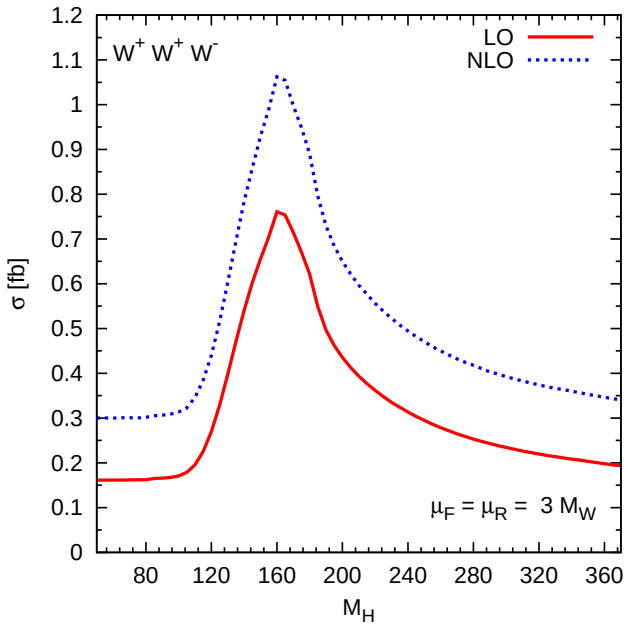
$W^+W^+W^-$ Production

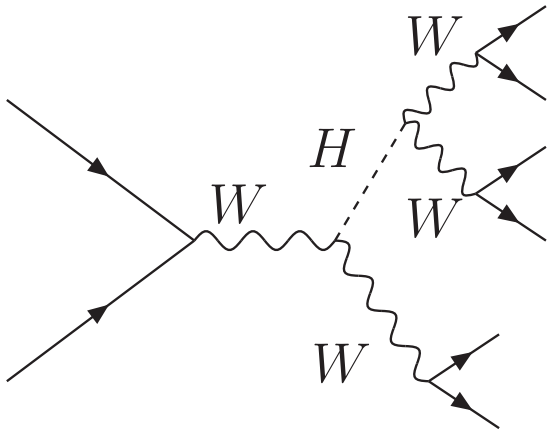




- At LO small μ_F-dependence, no $\alpha_s(\mu_R)$
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$
- Real emission contribution drives overall scale dependence at NLO (Real + finite collinear + substracted dipole terms)

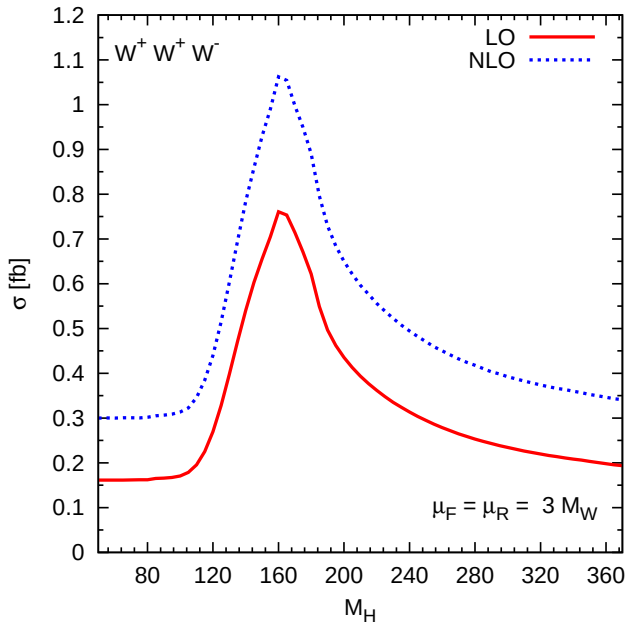
Higgs Mass Dependence

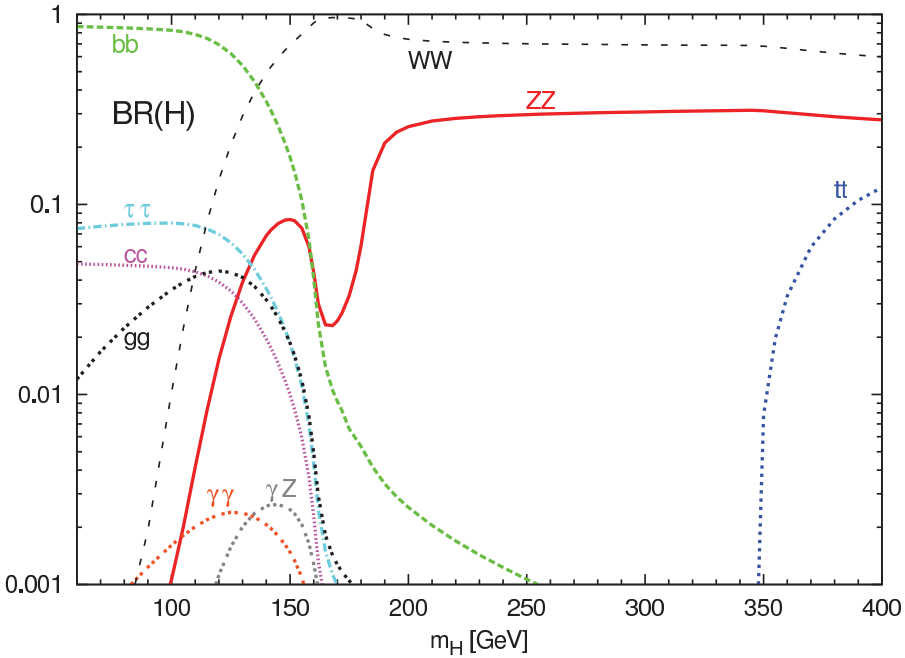




- Cross section reflects behavior of BR($H \to WW$)
- K-factor is reduced by the H contributions
  - $\to$ K-factor=1.3 for Higgs contributions.

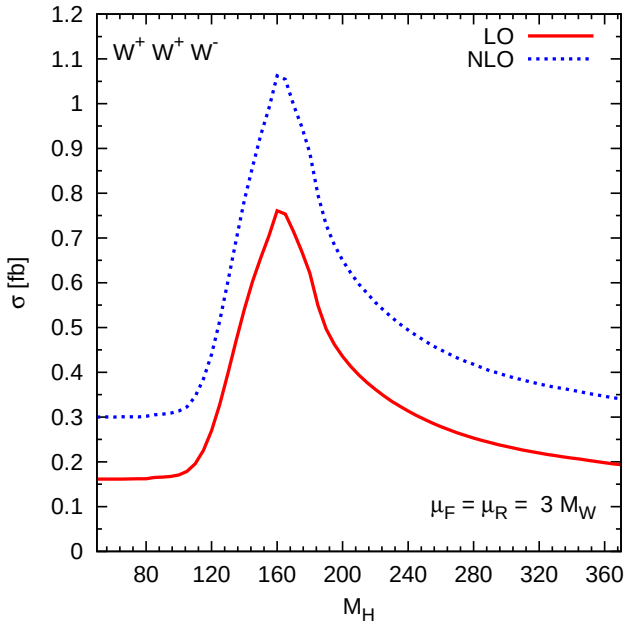
Higgs Mass Dependence

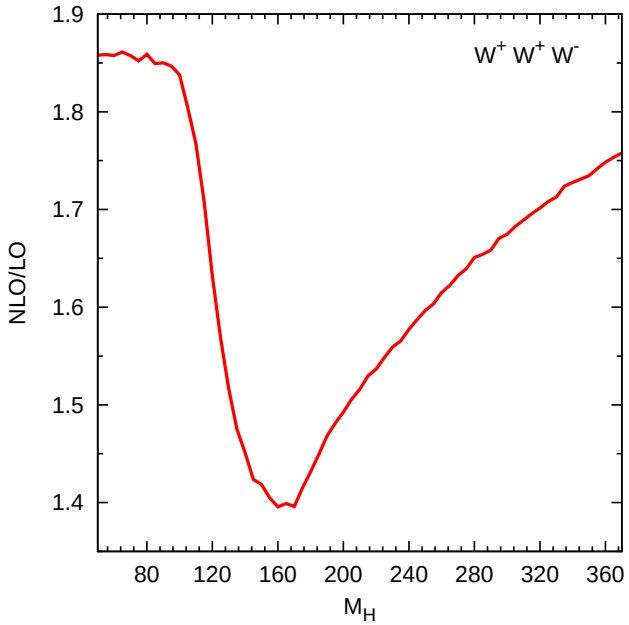




- Cross section reflects behavior of BR($H \to WW$)
- K-factor is reduced by the H contributions
  - $\to$ K-factor=1.3 for Higgs contributions.

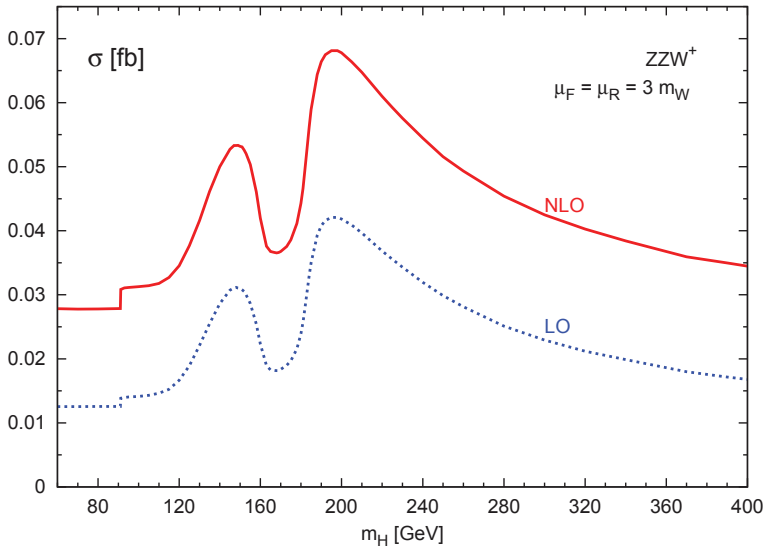
Higgs Mass Dependence

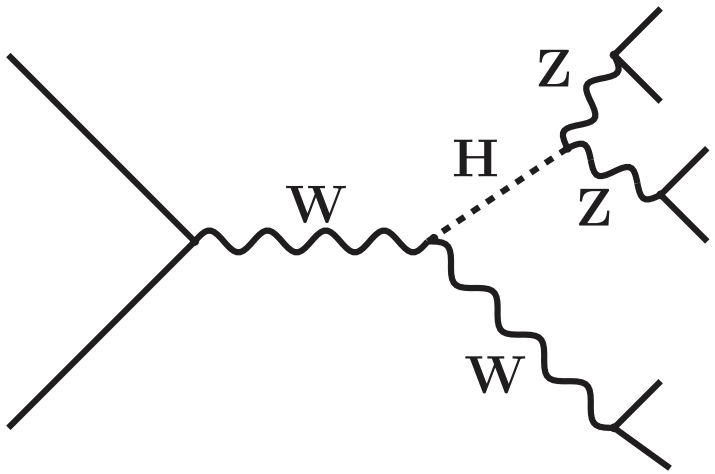




- Cross section reflects behavior of BR($H \to WW$)
- K-factor is reduced by the H contributions
  - $\to$ K-factor=1.3 for Higgs contributions.

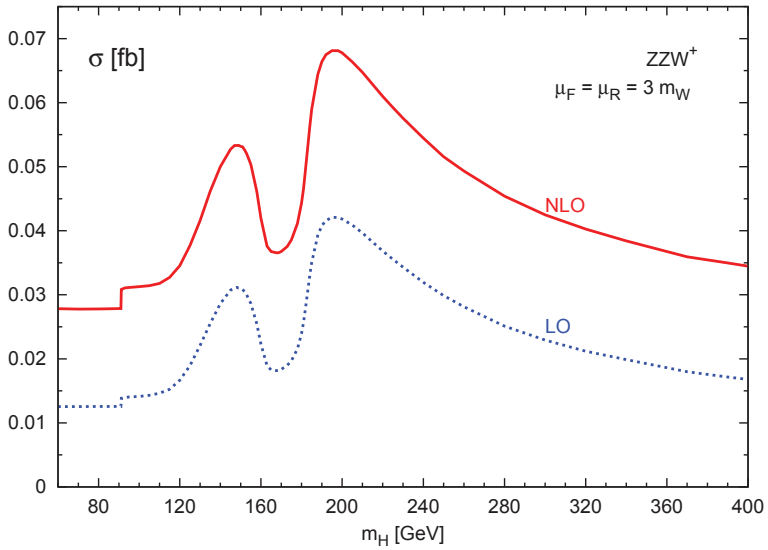
$ZZW^{\pm}$: Higgs Mass Dependence

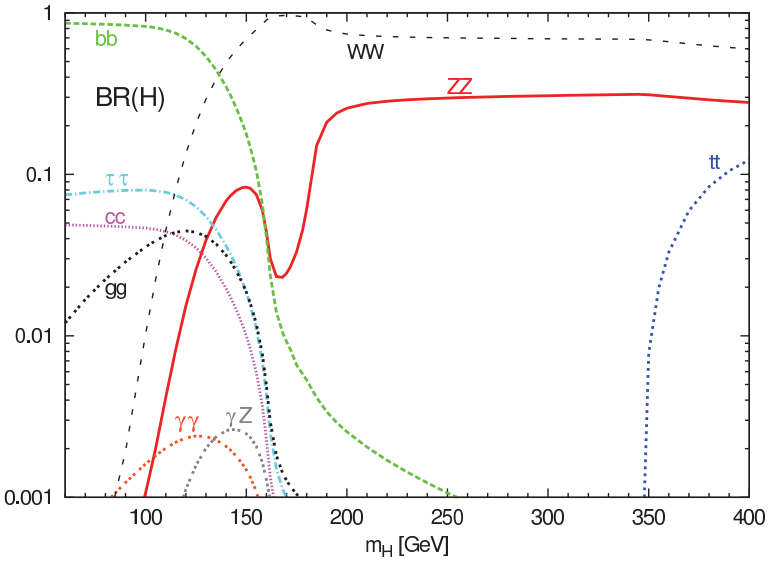




- Cross section reflects behavior of BR($H \to ZZ$)
- K-factor is reduced by the H contributions

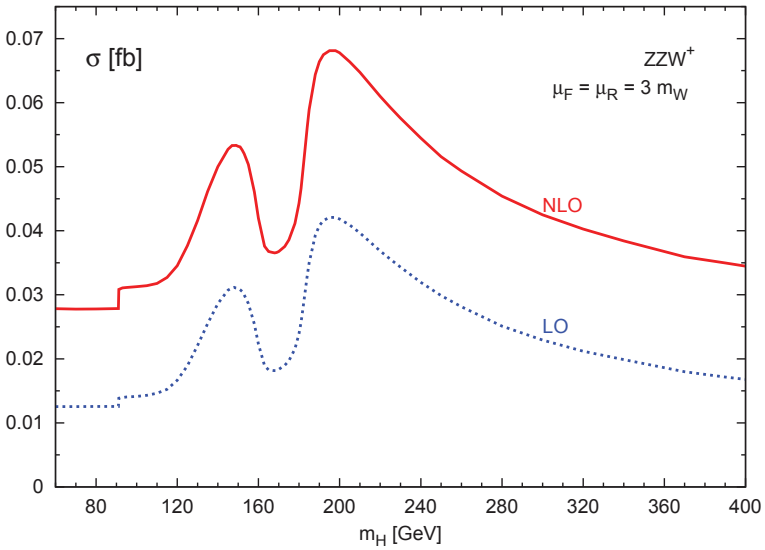
$ZZW^{\pm}$: Higgs Mass Dependence

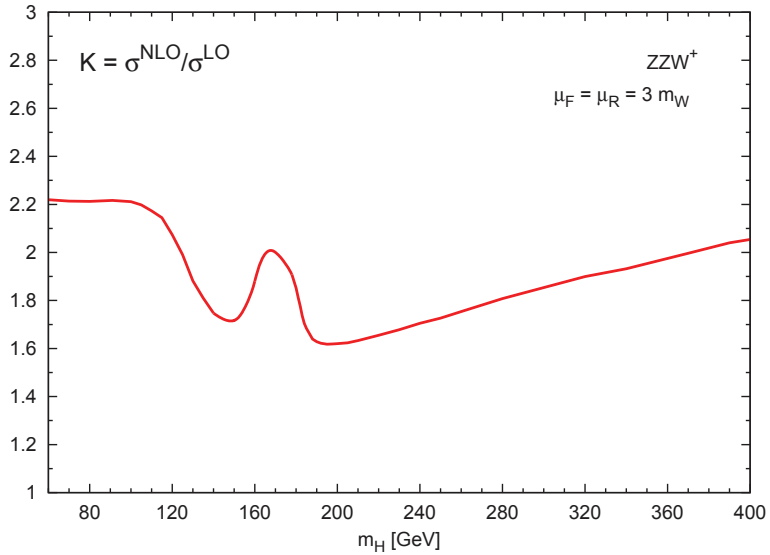




- Cross section reflects behavior of BR($H \to ZZ$)
- K-factor is reduced by the H contributions

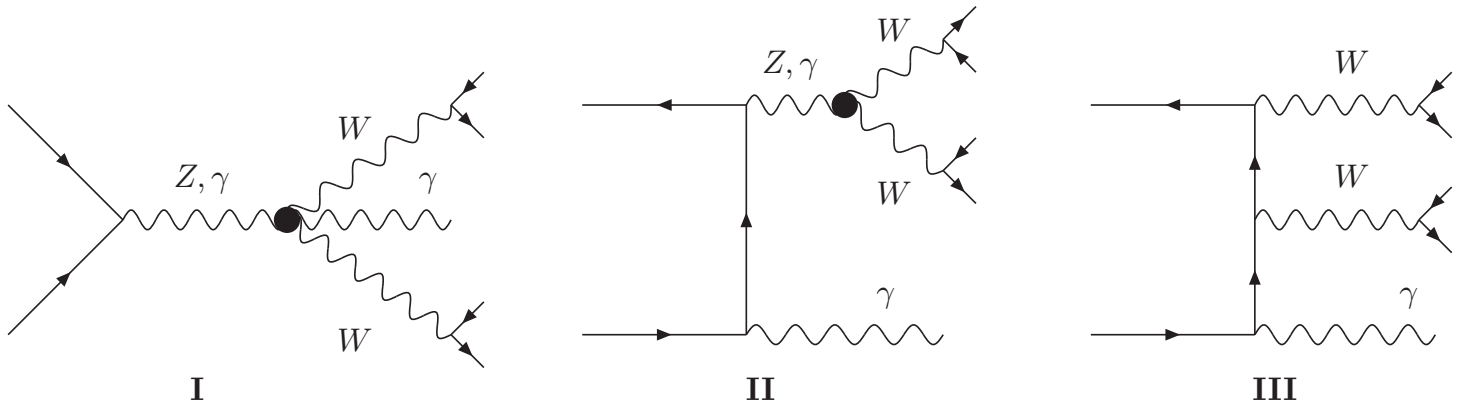
$ZZW^{\pm}$: Higgs Mass Dependence





- Cross section reflects behavior of BR($H \to ZZ$)
- K-factor is reduced by the H contributions

$W^+W^-\gamma$ ($ZZ\gamma$ and $W^\pm Z\gamma$) Production



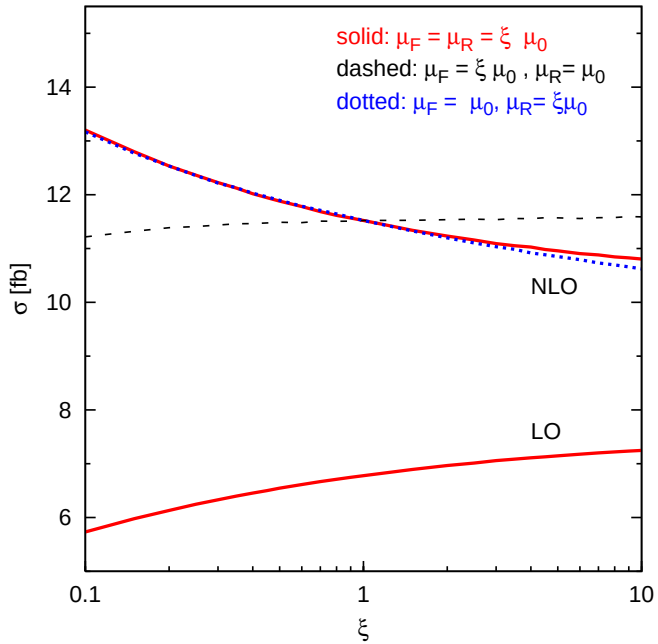
- Different infrared divergences structure of individual loop integrals but same final virtual expression.
- Photon isolation for the real emission contributions: use Frixione isolation

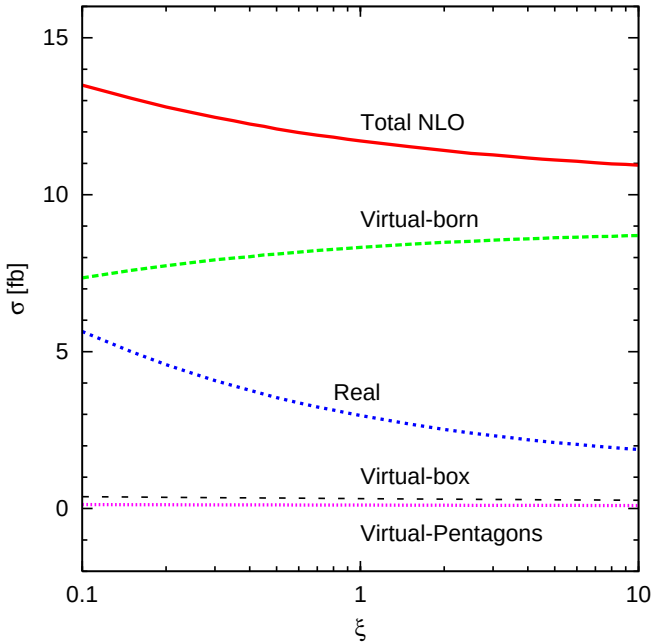
$$\Sigma_i E_{T_i}\,\theta(\delta - R_{i\gamma}) \leq p_{T_\gamma}\,\frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

- Final state radiation becomes important: adapt phase space

$W^+W^-\gamma$ Production

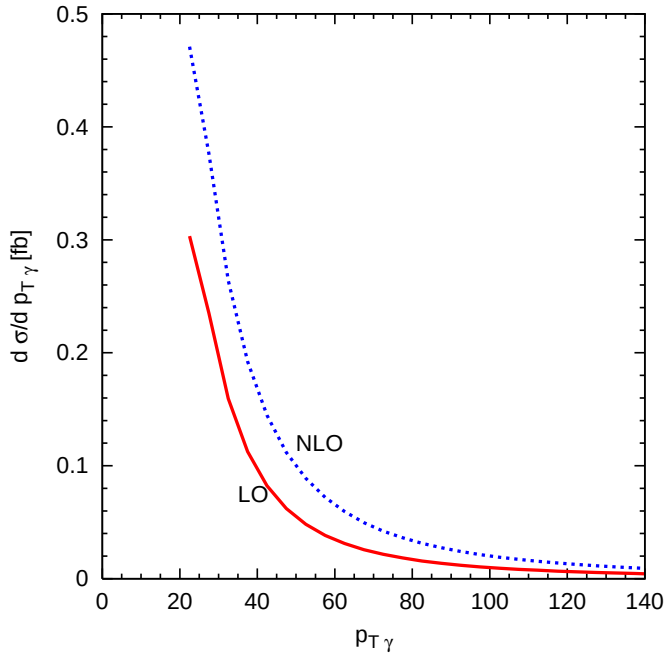
Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$

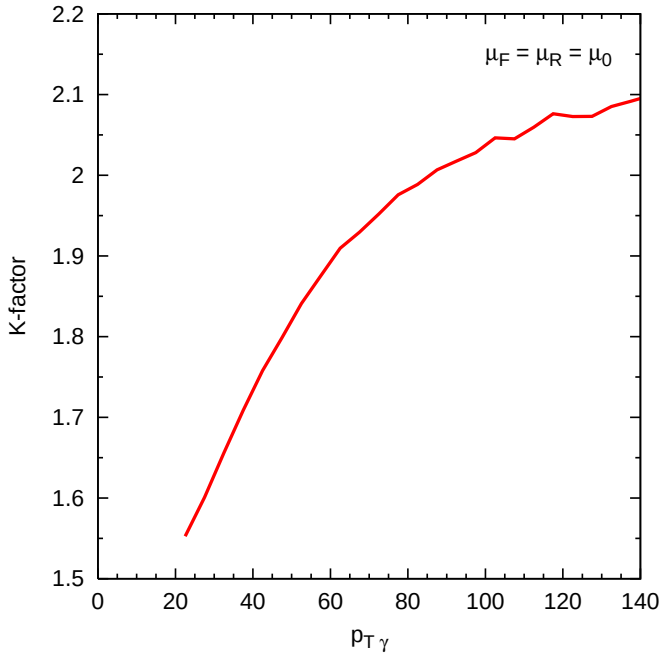




- LO scale variation smaller that NLO corrections
- NLO scale uncertainty due to real emission contributions

$W^+W^-\gamma$ Production



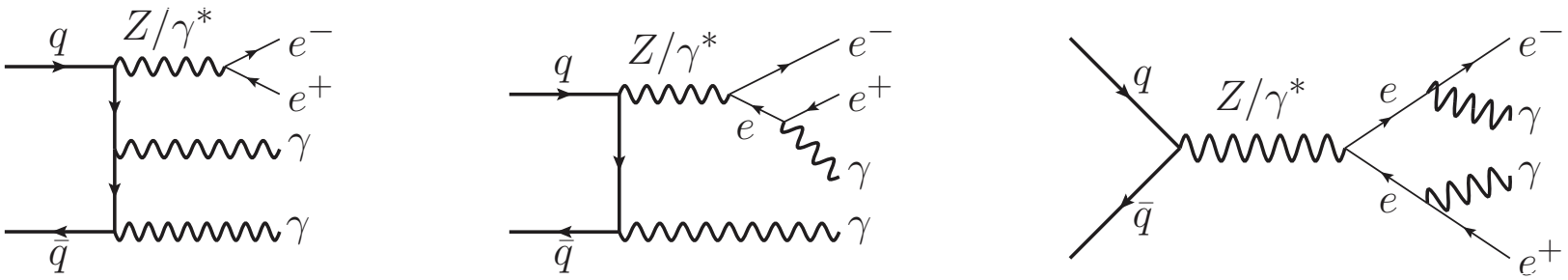


- Strong phase space dependence of K-factor
- No cte factor can be applied to correct the distributions

  $\rightarrow$ Devoted MC programs with flexible cut and distributions

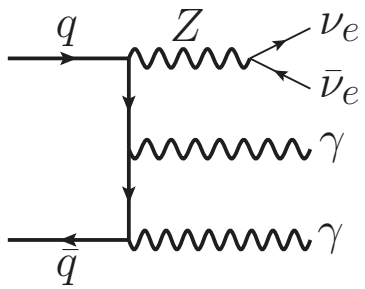
VBFNLO at http://www-itp.particle.uni-karlsruhe.de/vbfnlo/

$Z\gamma\gamma$ Production



- Different infrared divergences structure of individual loop integrals but same final virtual expression.
- Photon isolation from jets for real emission contributions: use Frixione isolation
- Final state radiation becomes important: adapt phase space

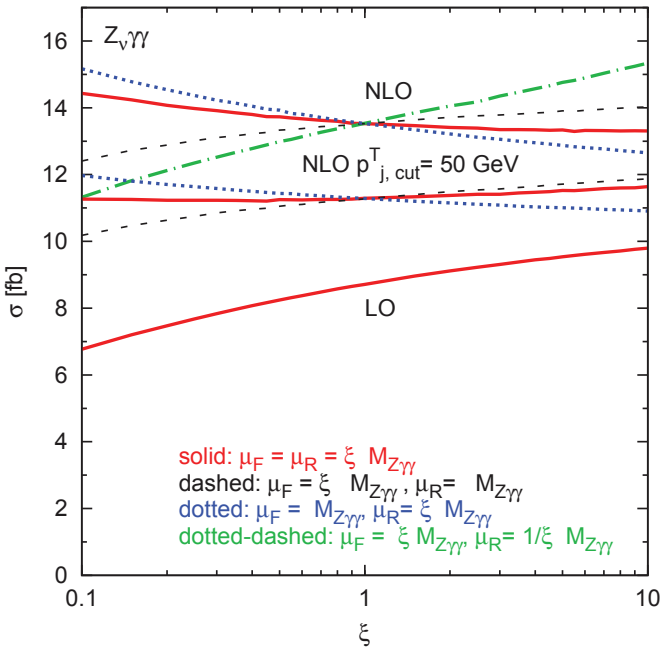
$Z\gamma\gamma$ Production

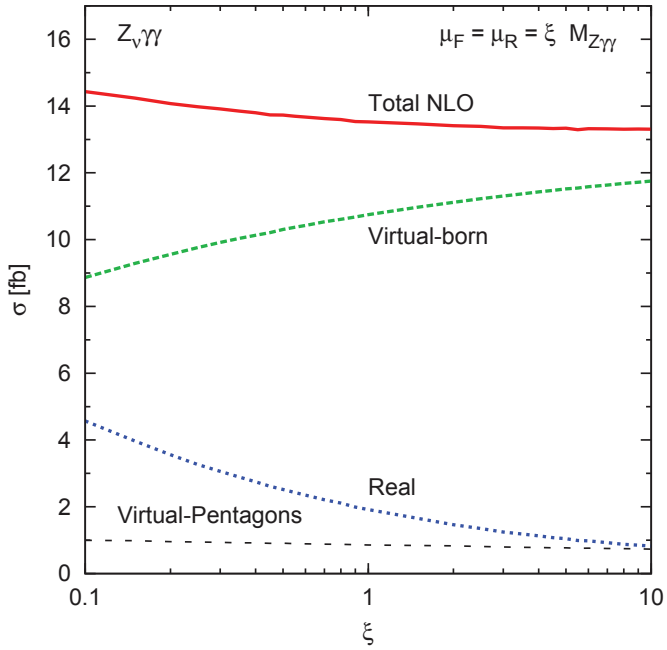


- Different infrared divergences structure of individual loop integrals but same final virtual expression.
- Photon isolation from jets for real emission contributions: use Frixione isolation
- Final state radiation becomes important: adapt phase space

$Z\gamma\gamma$ Production

Background to new physics (LSP neutralino), AQC

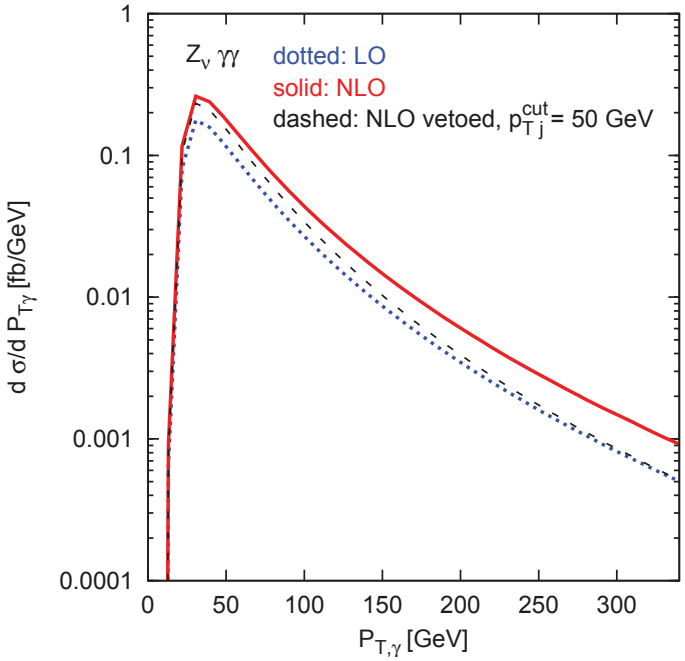


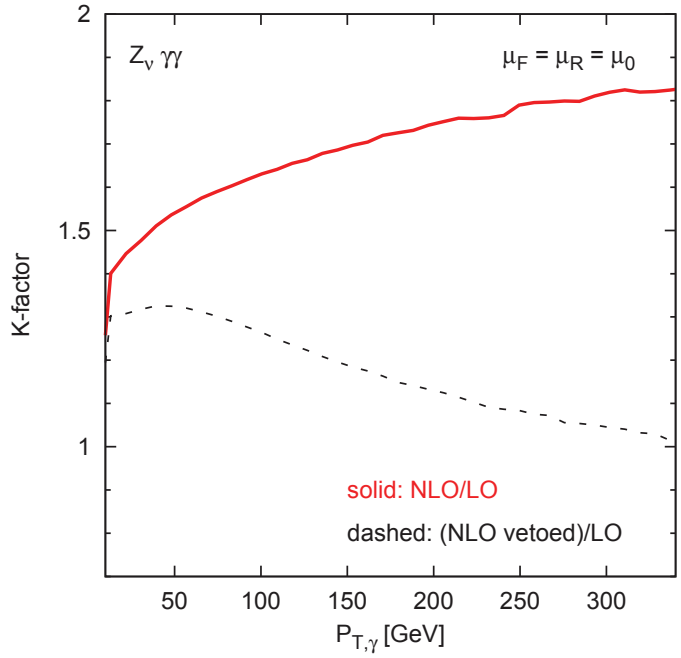


- Large K factor around 1.75
- Real corrections dominate overall scale uncertainty

$Z\gamma\gamma$ Production

Background to new physics (LSP neutralino).

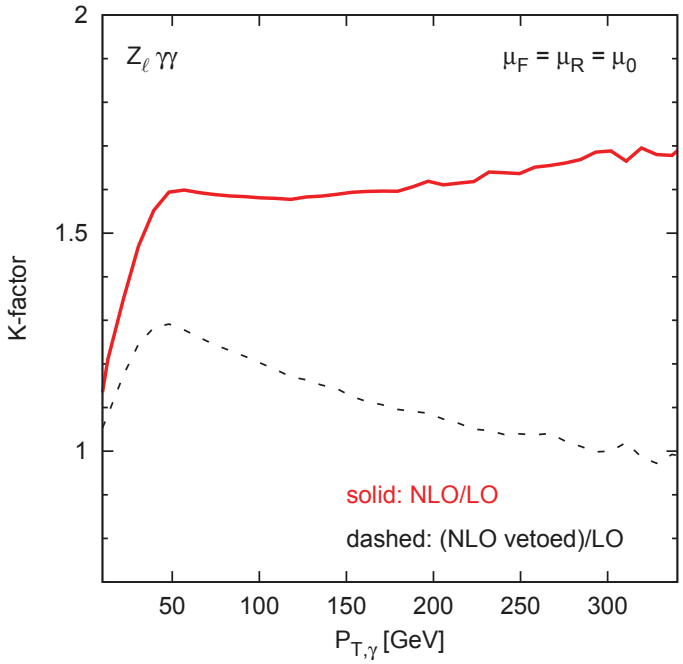


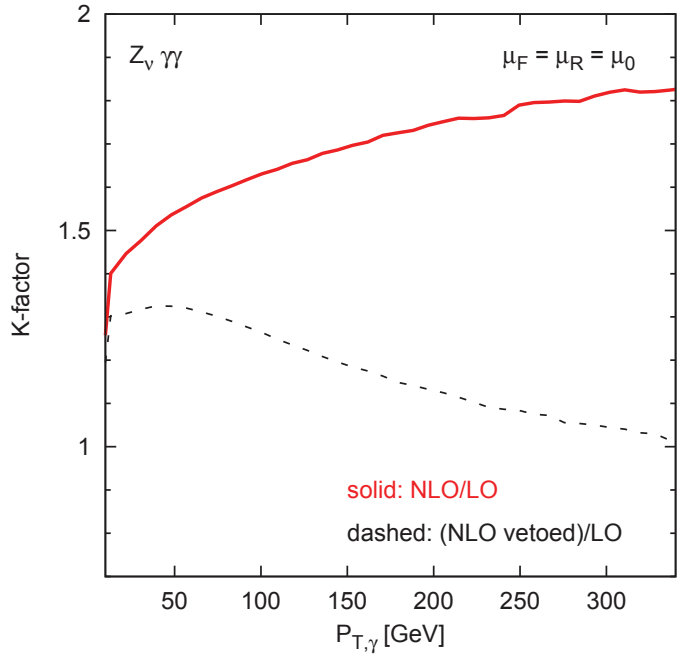


- Real corrections dominate overall scale uncertainty

$Z\gamma\gamma$ Production

Background to new physics (LSP neutralino).

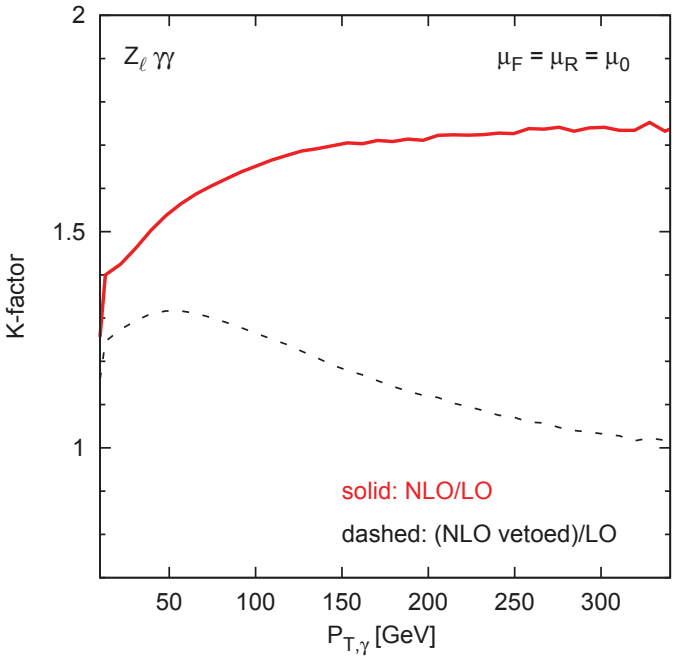


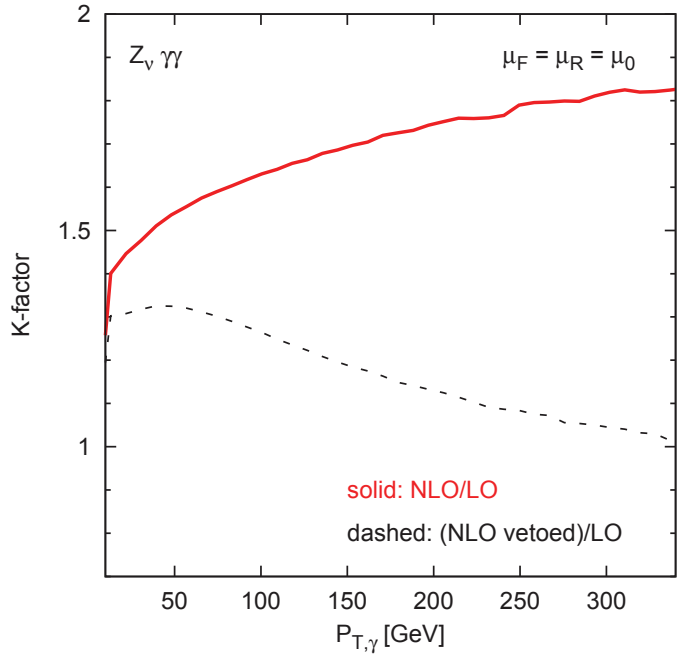


- Real corrections dominate overall scale uncertainty

$Z\gamma\gamma$ Production

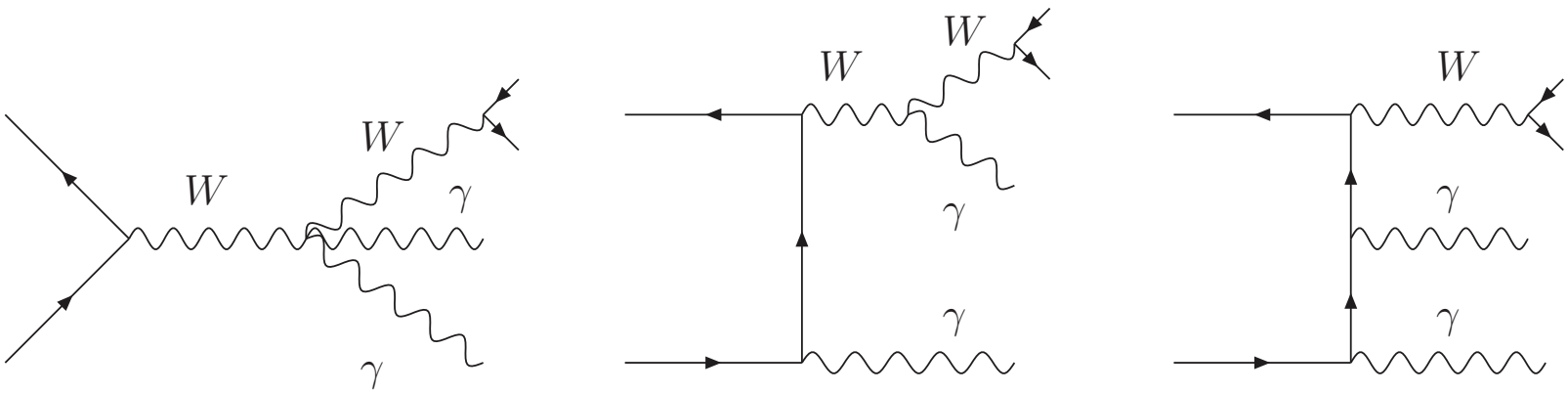
Background to new physics (LSP neutralino).





- Real corrections dominate overall scale uncertainty

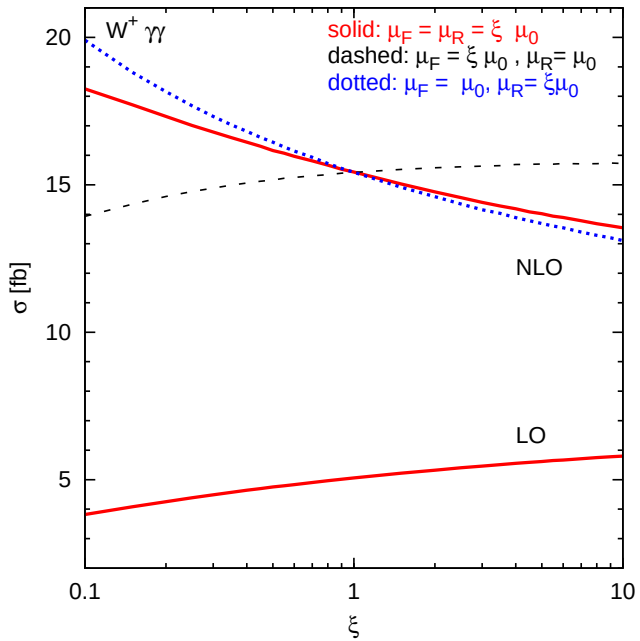
$W^+\gamma\gamma$ Production

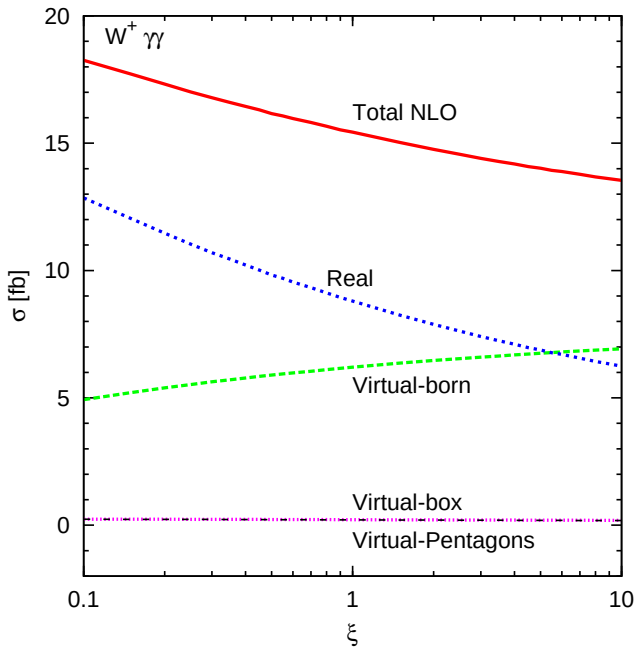


- Different infrared divergences structure of individual loop integrals but same final virtual expression.
- Photon isolation from jets for real emission contributions: use Frixione isolation
- Final state radiation becomes important: adapt phase space

$W^{\pm}\gamma\gamma$ Production

Background to new physics (LSP gravitino). Quartic Couplings

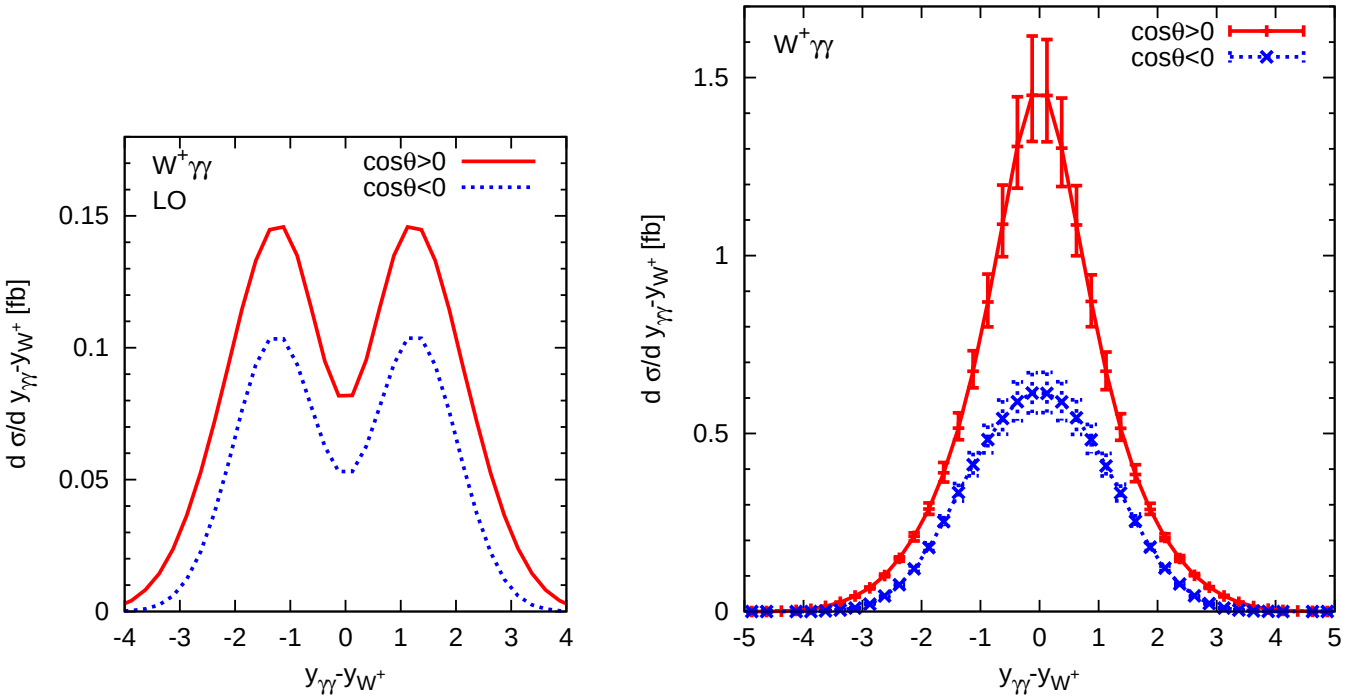




- Large K factor around 3.3!
- Real corrections dominate overall scale uncertainty

$W^{\pm}\gamma\gamma$ Production

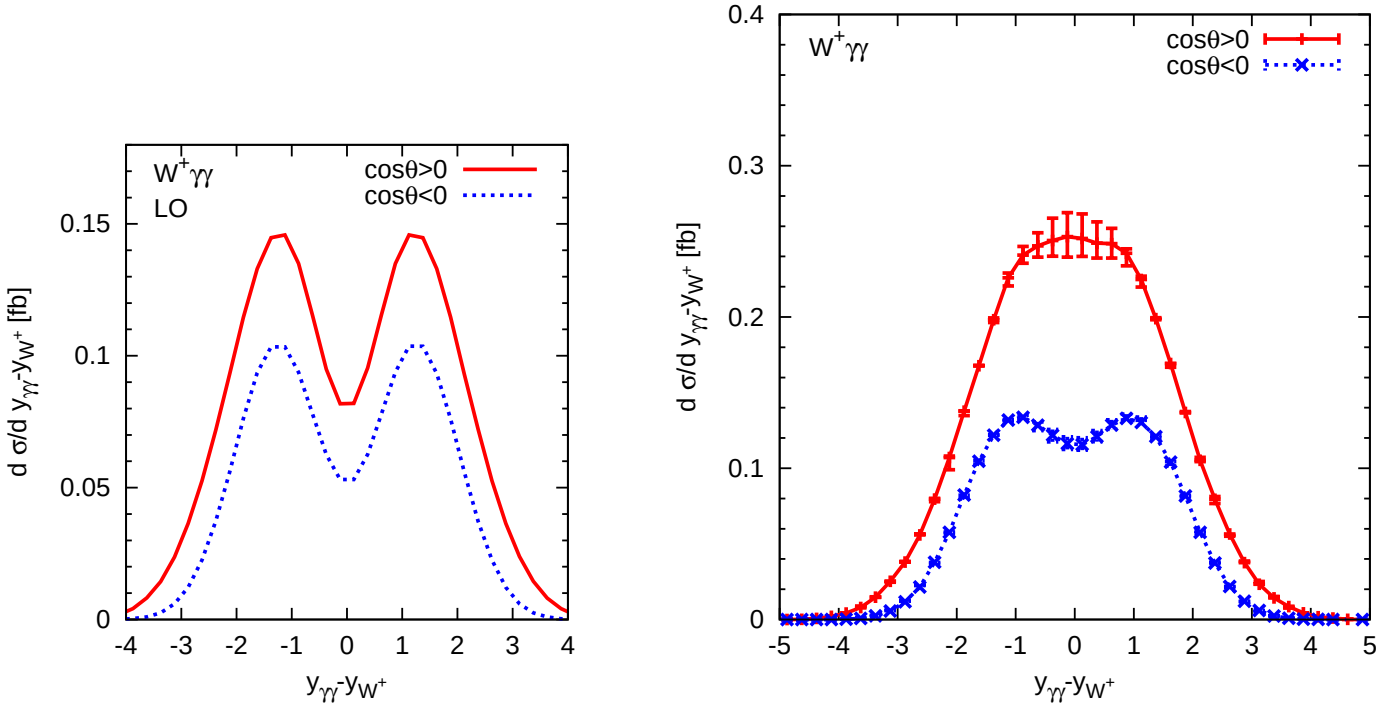
LO suppressed by Radiation Zero



- K-factor in central region around 18

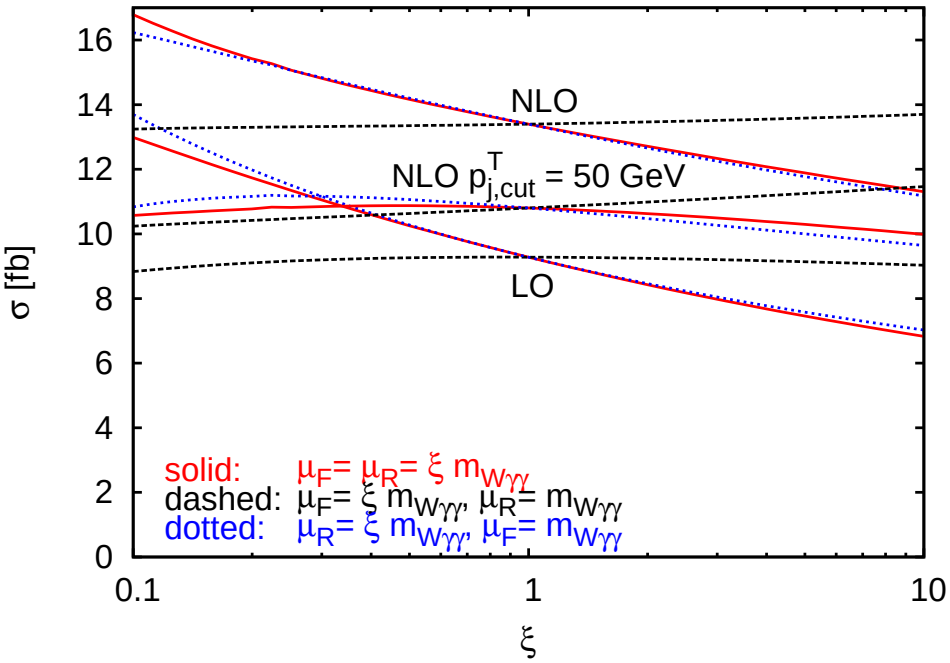
$W^{\pm}\gamma\gamma$ Production

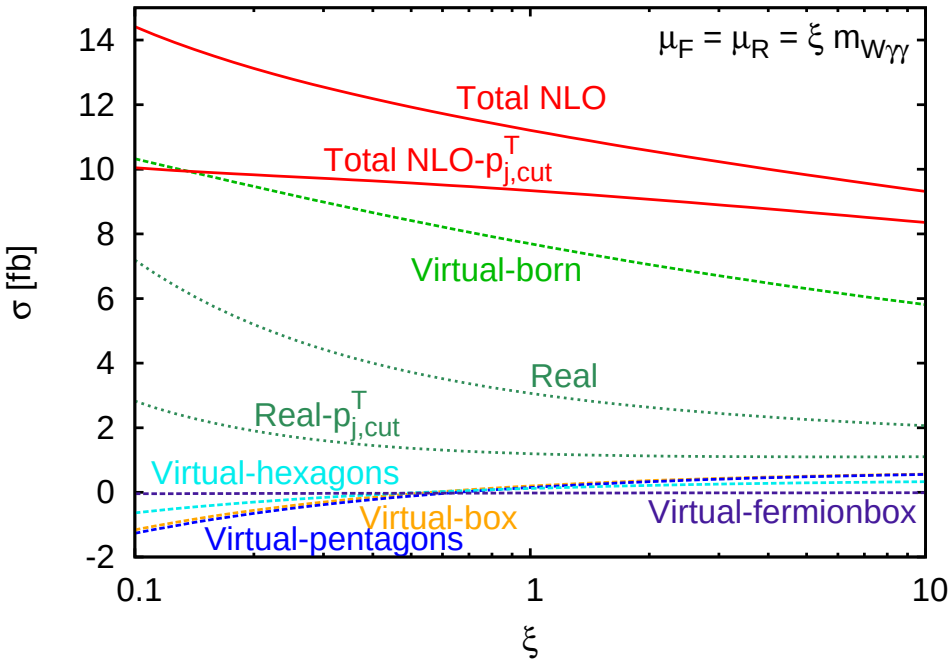
LO suppressed by Radiation Zero



- Veto might help to detect Radiation Zero
- $W\gamma\gamma + j$ at NLO: Towards NNLO of $W\gamma\gamma$

$W^{\pm}\gamma\gamma + j$ Production

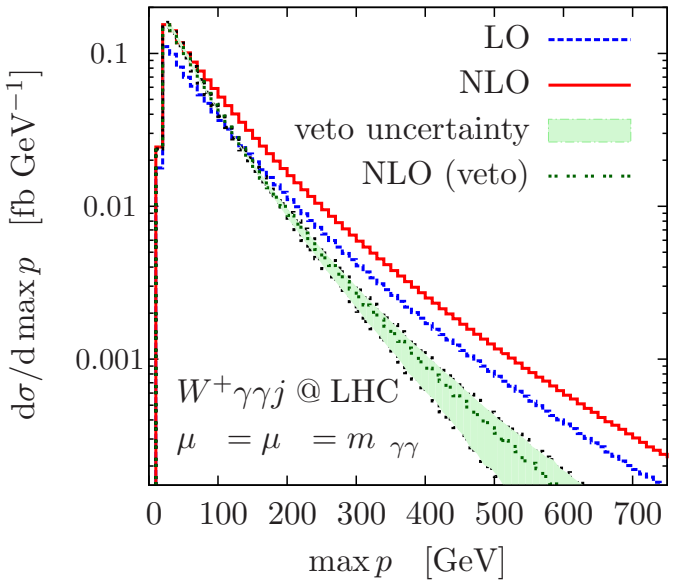


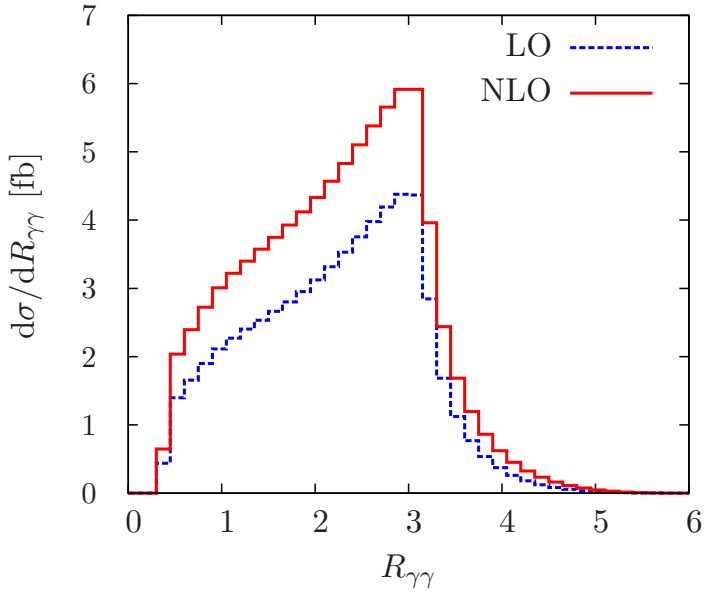


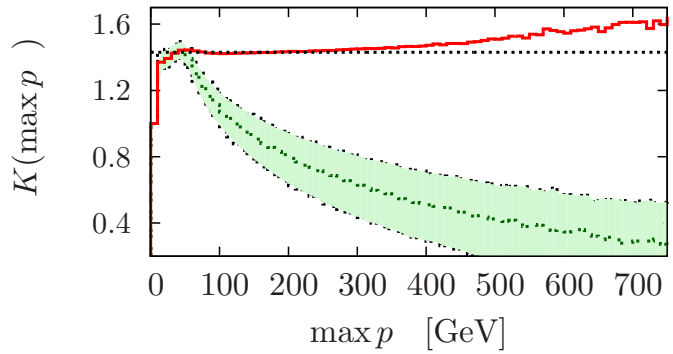
	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$K = \sigma^{\rm NLO}/\sigma^{\rm LO}$	
$W^{\pm}\gamma\gamma$+jet	1.1911(1)	1.7584(6,0.6)	1.48	Tevatron
$W^{+}\gamma\gamma$+jet	4.6400(1)	6.5028(6,6)	1.40	LHC
$W^{-}\gamma\gamma$+jet	3.8030(1)	5.544(1,0.3)	1.46	

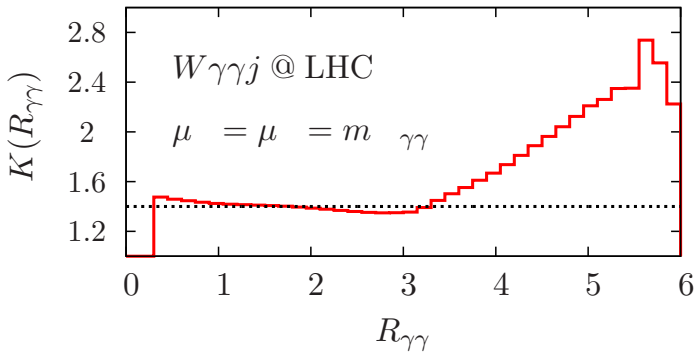
$W^{\pm}\gamma\gamma$+jet:24h in 1 Core: $\sigma^{\rm NLO}$= 6.50(2,0.006) [fb] 0.3%

$W^+\gamma\gamma + j$ Production



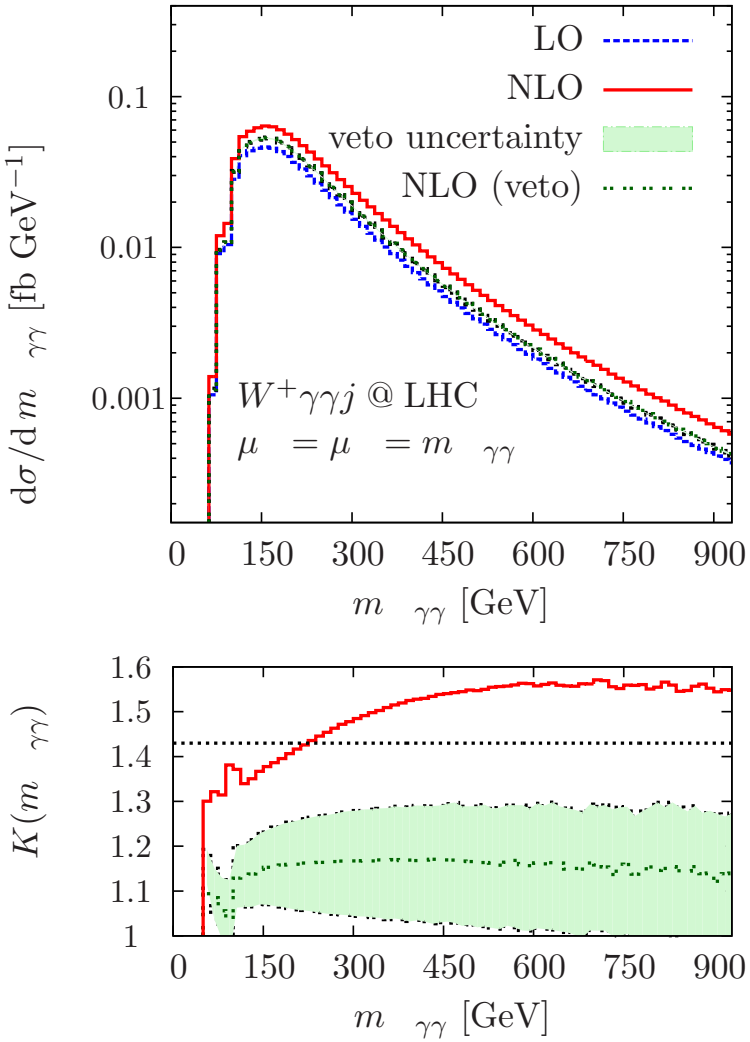






- Vetoed badly modelled!
- Additional jet radiation affects LO kinematics

$W^+\gamma\gamma + j$ Production



- Sizeble corrections
- If not included: QCD corrections fake anomalous couplings

→ Devoted MC programs with flexible cut and distributions

- Potentially LARGE NNLO corrections: $K_{W\gamma\gamma j}$=1.4

→ $(NNLO/NLO)_{W\gamma\gamma} \sim (1.4)$

- Similar to $\gamma\gamma$@ NNLO

Conclusions

- NLO QCD corrections are large: $40-70\%$ for VVV, for $W\gamma\gamma$ 300%
- Scale dependence at the 10 % level
- Strong phase space dependence
- $W\gamma\gamma j$

VBFNLO: Next release in Winter 2013(See talk by M.Rauch)

http://www.itp.kit.edu/$\sim$vbfnloweb/wiki/doku.php