NLO QCD + EW + decays prediction to ZZ + jet/γ productions at LHC

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Outline

一. • Motivations

二. • Calculation details

三. • Numerical results

四. • Summary

I. Motivations

LHC: Precision measurements will be possible in Run2

ZZ+jet: A useful background process for Higgs-boson production.

ZZ+ γ: Help for the determination of quartic gauge boson coupling.

Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\gamma\gamma$	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

Table 3: Wishlist part 3 – Electroweak Gauge Bosons (V = W, Z)

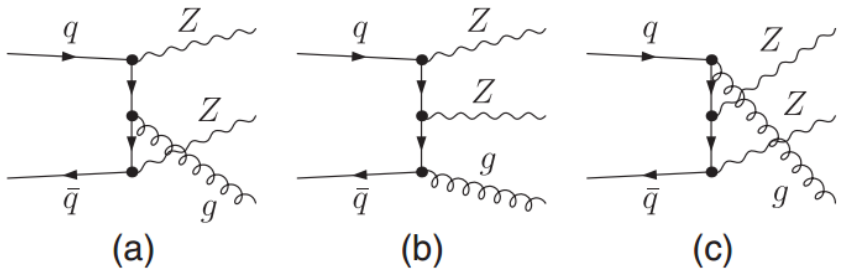
Les Houches 2015: Physics at TeV Colliders
Standard Model Working Group Report

High-precision NLO prediction needed !

$pp \to V + j$	$d\sigma$	N^2LO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
$pp \to V + 2j$	$d\sigma$ $d\sigma$	NLO_{QCD}+ decays NLO_{EW}+ decays	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
$pp \to VV' + 1, 2j$	$d\sigma$ $d\sigma$	NLO_{QCD}+ decays NLO_{EW}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to VV'V''$	$d\sigma$ $d\sigma$	NLO_{QCD} NLO_{EW}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to \gamma\gamma$	$d\sigma$	N^2LO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}
$pp \to \gamma\gamma + j$	$d\sigma$	NLO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}

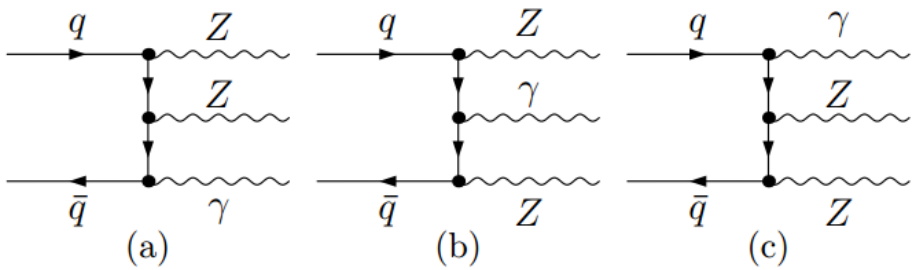
Table I.2: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$.

II. Calculation details- **LO contributions**



3 partonic processes at $\mathcal{O}(\alpha_{ew}^2 \alpha_s)$

$q\bar{q} \rightarrow ZZ+g$; $qg \rightarrow ZZ+q$; $\bar{q}g \rightarrow ZZ+\bar{q}$



Only 1 partonic process at $\mathcal{O}(\alpha_{ew}^3)$

$q\bar{q} \rightarrow ZZ+\gamma$

Integrated cross section:

$$\sigma^{LO}(pp \rightarrow ZZ + jet/\gamma) = \sum_{a,b} \int d\,x_1 dx_2\, f_{a/p}(x_1) f_{b/p}(x_2) \hat{\sigma}^{LO}_{ab \rightarrow ZZ+jet/\gamma}$$

$$\boxed{\sigma^{NLO} = \sigma^{LO} + \sigma^{vir} + \sigma^{real}}$$

II. Calculation details- **NLO QCD calculations**

- Corrections of NLO QCD could be large (typically at $\mathcal{O}(10\%)$) !
- Necessary to reduce the scale dependence !

State of the art (NLO QCD):

ZZ+jet: T. Binoth, T. Gleisberg, S. Karg, N. Kauer, and G. Sanguinetti, **Phys. Lett. B683, 154 (2010).**

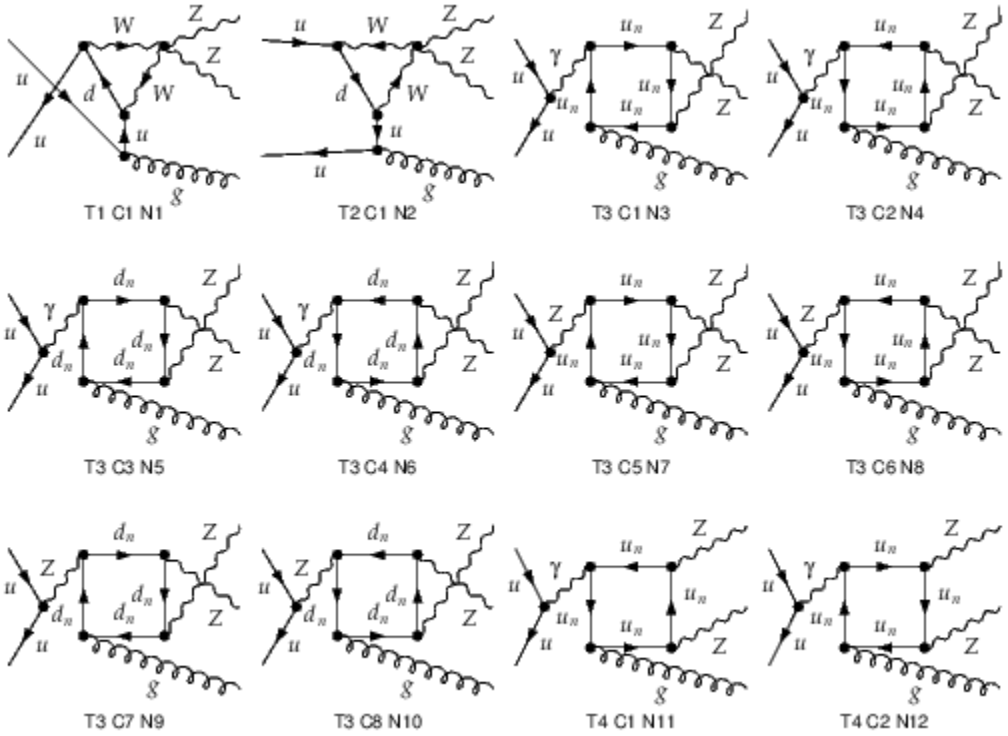
ZZ+ γ: G. Bozzi, F. Campanario, V. Hankele and D. Zeppenfeld, **Phys. Rev. D 81, 094030 (2010)**.

What next …

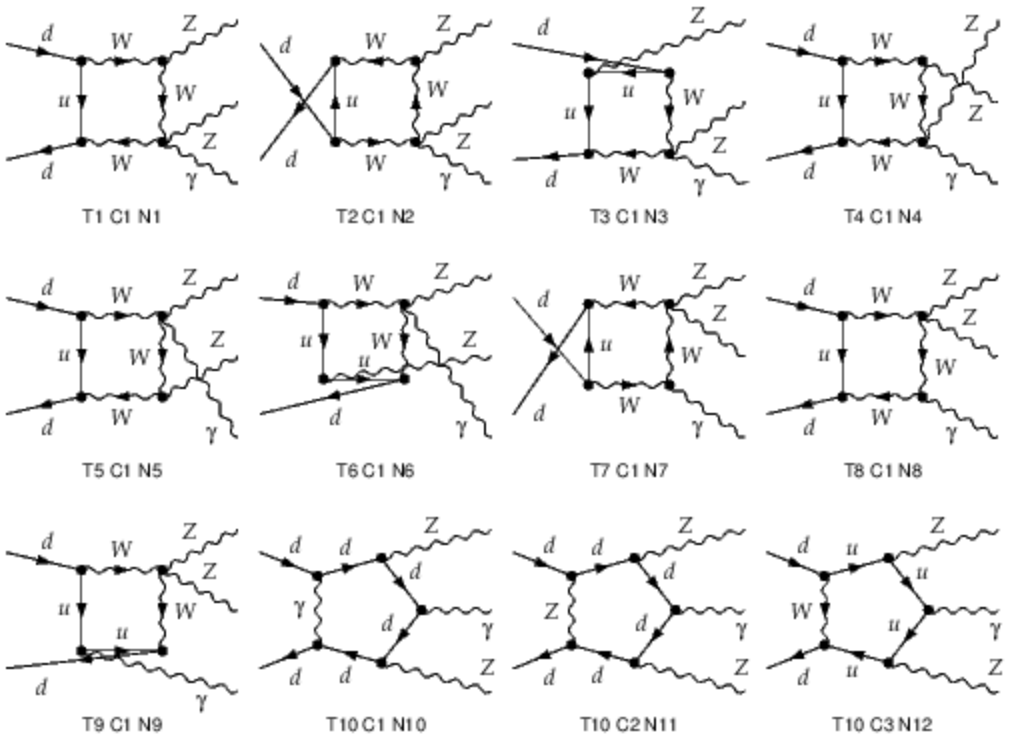
$\mathcal{O}(\alpha_s) \sim \mathcal{O}(\alpha_{ew}^2)$

The **NLO EW** correction becomes mandatory !

II. Calculation details-**EW Virtual corrections**



$pp \to ZZ + jet$

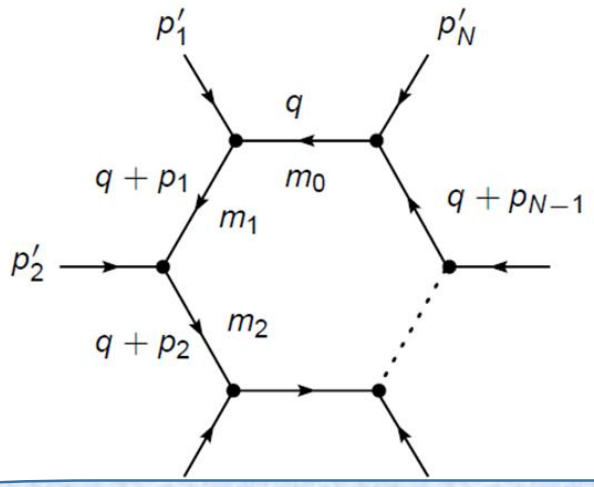


$pp \to ZZ + \gamma$

Roughly 2K loop diagrams for each !

II. Calculation details-EW Virtual corrections

Loop amplitudes tensor reduction:



$$T^{N}_{\mu_1 \ldots \mu_M} = \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D q \frac{q_{\mu_1} \ldots q_{\mu_M}}{D_1 \ldots D_{N-1}} \quad \text{with } D_i = \left[(q + p_i)^2 - m_i^2 \right]$$

N = 5: Reduced to 4-point integrals based on approach raised by Denner- Dittmaier.

N$\leqslant 4$: Standered PV dimensional tensor reduction.

$$F^{N}_{j_1 \ldots j_M} \sim \frac{N(p,m)}{(detG_N)^M} \rightarrow 0$$: **Numerical Instability !**

$$G_N = \begin{pmatrix} 2p_1p_1 & \cdots & 2p_1p_{N-1} \\ \vdots & \ddots & \vdots \\ 2p_{N-1}p_1 & \cdots & 2p_{N-1}p_{N-1} \end{pmatrix}$$

Inhouse improved LoopTools package

$$\frac{\det(G_3)}{(2p^2_{max})^3} < 10^{-5}?$$

YES, Quadruple arithmetic

NO, Double arithmetic

II. Calculation details-coupling scheme selection

❑ EW input-parameter scheme

$$\alpha(0) \rightarrow \alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\theta_W , \quad \delta z_e \rightarrow \delta z_e - \frac{1}{2}\Delta r$$

for collinear photon emission

$\alpha_{G_\mu} = \alpha_0(1+\Delta r) + \Delta\alpha^3$

absorb high order universal effects due to Δr

	LO	NLO QCD	NLO EW
$pp \rightarrow ZZ + jet$	$\alpha_{G_\mu}^2 \alpha_s$	$\alpha_{G_\mu}^2 \alpha_s^2$	$\alpha_{G_\mu}^3 \alpha_s$
$pp \rightarrow ZZ + \gamma$	$\alpha_{G_\mu}^2 \alpha_0$	$\alpha_s \alpha_{G_\mu}^2 \alpha_0$	$\alpha_{G_\mu}^3 \alpha_0$

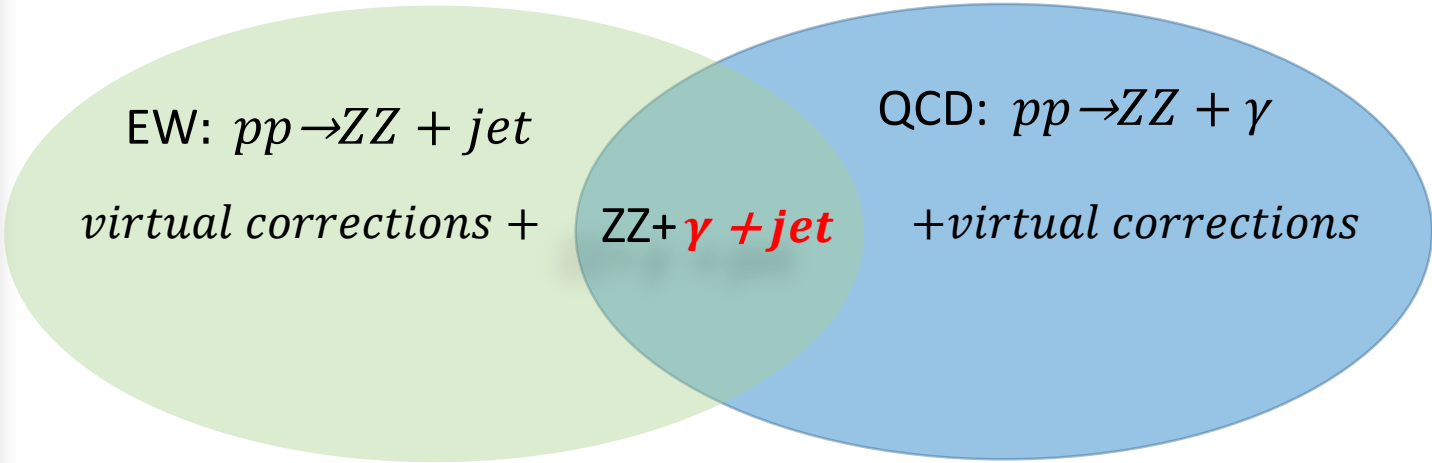
II. Calculation details-real emission corrections

QCD emission

$pp \to ZZ + jet \;\; + jet$ $\qquad$ $pp \to ZZ + \boxed{\boldsymbol{\gamma} + \boldsymbol{jet}}$

EW emission

$pp \to ZZ + \boxed{\boldsymbol{jet} \;\; + \boldsymbol{\gamma}}$ $\qquad$ $pp \to ZZ + \gamma + \gamma$



Problem: Identify the FS signal as ZZ+ jet or ZZ+ γ ?

II. Calculation details-IR-safe events identification

NOTE: Take photon emission for $pp \to ZZ + jet$ as example

QCD IR divergence of $pp \to ZZ + \gamma$

W.r.t quark jet,

- Recombination q + $\gamma \to \widetilde{q\gamma}$ is necessary for Collinear singularities cancelation (**KLN theorem**)

BUT, gluon jet should treated equivalence with quark jet

- Recombination q +g $\to \widetilde{g\gamma}$ is also needed ⇒ the $E_g \to 0$ leads to **Soft gluon poles !!!**

Solution 1:

Construct an adapted definition of the allowed hadronic energy fraction in a collinear jet-photon system.

Frixione isolation: S. Frixione, Phys. Lett. B 429 396 (1998)

$$p_{T,jet} > \chi(\delta), \qquad \chi(\delta) = E_{T,\gamma}\, \epsilon_\gamma \left(\frac{1-\cos(\delta)}{1-\cos(\delta_0)}\right)^n$$

II. Calculation details-IR-safe events identification

Solution 2:

- ✓ Take jet energy fraction $\frac{E_{jet}}{E_{jet}+E_{\gamma}} > 0.7$, extract $ZZ + jet$ events from inclusive events.
- ✓ The residual collinear singularities absorbed to renormalized photon fragmentation function .

----E.W.N. Glover and A.G. Morgan, Z. Phys. C 62. 311(1994)

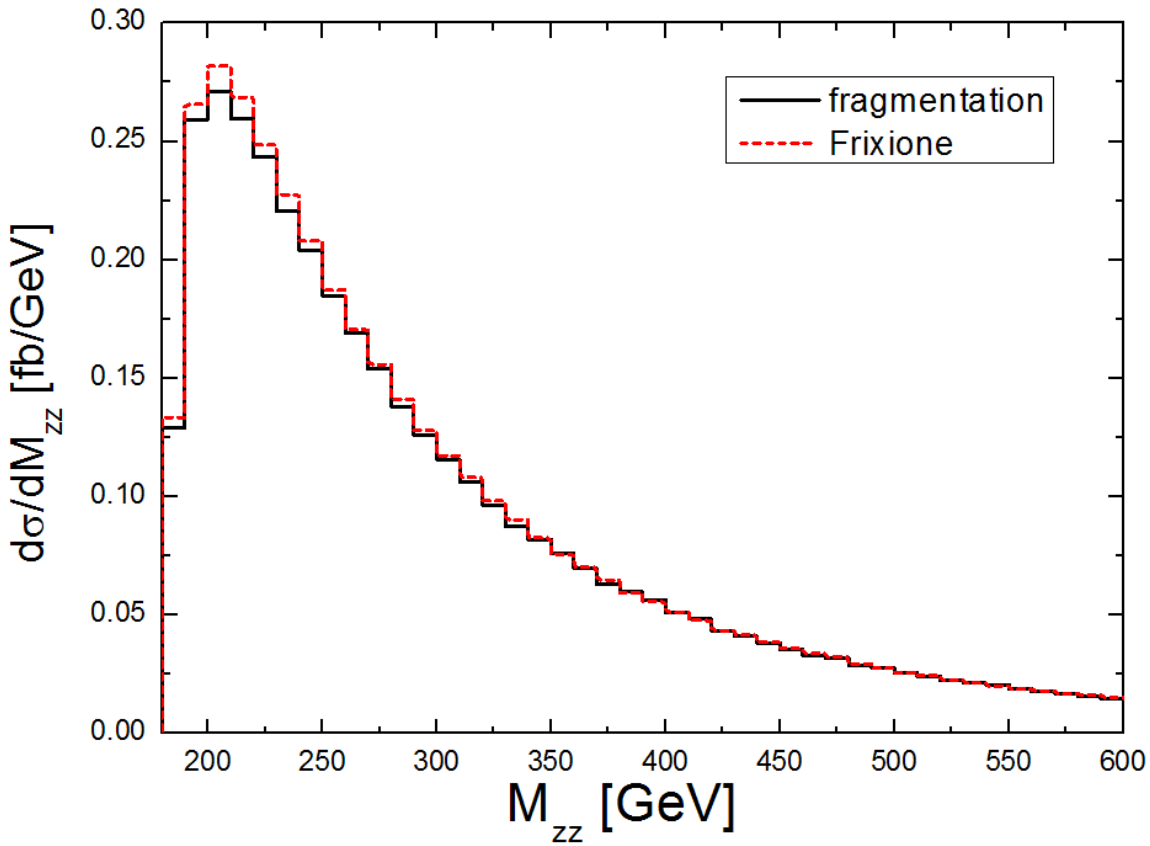
$$\mathcal{D}_{q\to\gamma}(z_\gamma) = -\frac{Q_q^2\alpha}{2\pi}\frac{1}{\epsilon}\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{\delta_c\hat{s}}\right)^{\epsilon}[z_\gamma(1-z_\gamma)]^{-\epsilon}[P_{\gamma q}(z_\gamma)-\epsilon z_\gamma] + D^{\text{bare}}_{q\to\gamma}(z_\gamma).$$

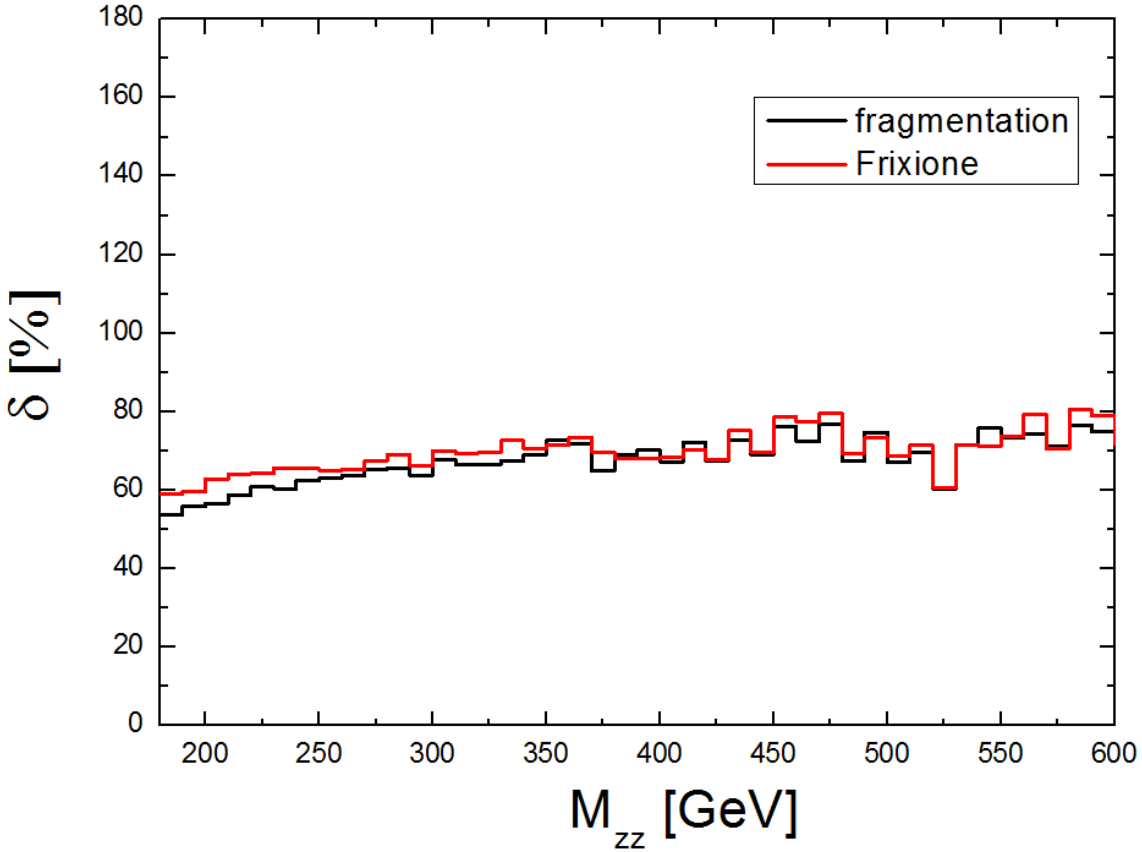
$$D^{\text{bare}}_{q\to\gamma}(z_\gamma) = \frac{Q_q^2\alpha}{2\pi}\frac{1}{\epsilon}\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^{\epsilon}P_{\gamma q}(z_\gamma) + D_{q\to\gamma}(z_\gamma,\mu_f)$$

- ❖ Non-perturbative fragmentation contributions has been determined by LEP experiment.

II. Calculation details-IR-safe events identification

Typical deviation like ..... (NLO QCD corrections to $pp \rightarrow ZZ + \gamma$)





II. Calculation details-General set up

QCD & EW corrections combined in approximate multiplying scheme:

RATHER:

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}}[(1+\delta_{\mathrm{QCD}})(1+\delta_{\mathrm{EW}}) + \boxed{\delta_{\gamma\text{-ind}}}$$
$$= \sigma^{\mathrm{LO}}(1+\delta_{\mathrm{NLO}}).$$

Inclusion of photon density in NNPDF ...

$$\sigma_{\gamma\text{-ind}} = \sigma^{0}_{\gamma\text{-ind}} + \Delta\sigma^{\mathrm{NLO\,QCD}}_{\gamma\text{-ind}}$$

(α_{ew}^3) $(\alpha_{ew}^3\alpha_s)$

THAN:

$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \Delta\sigma^{\mathrm{QCD}} + \Delta\sigma^{\mathrm{EW}} + \Delta\sigma^{\gamma-\mathrm{ind}}$$

Mixed $O(\alpha_s\alpha_{ew})$ contributions may important in describing the large logarithms and/or kinematical effects ! ! !

III. Numerical results-$pp \to ZZ + jet$

$\sigma^{LO} = 2.1348^{+9.8\%}_{-8.5\%}$ pb, $\sigma^{NLO} = 3.087^{+5.5\%}_{-4.7\%}$ pb. → Reduced scale dependence

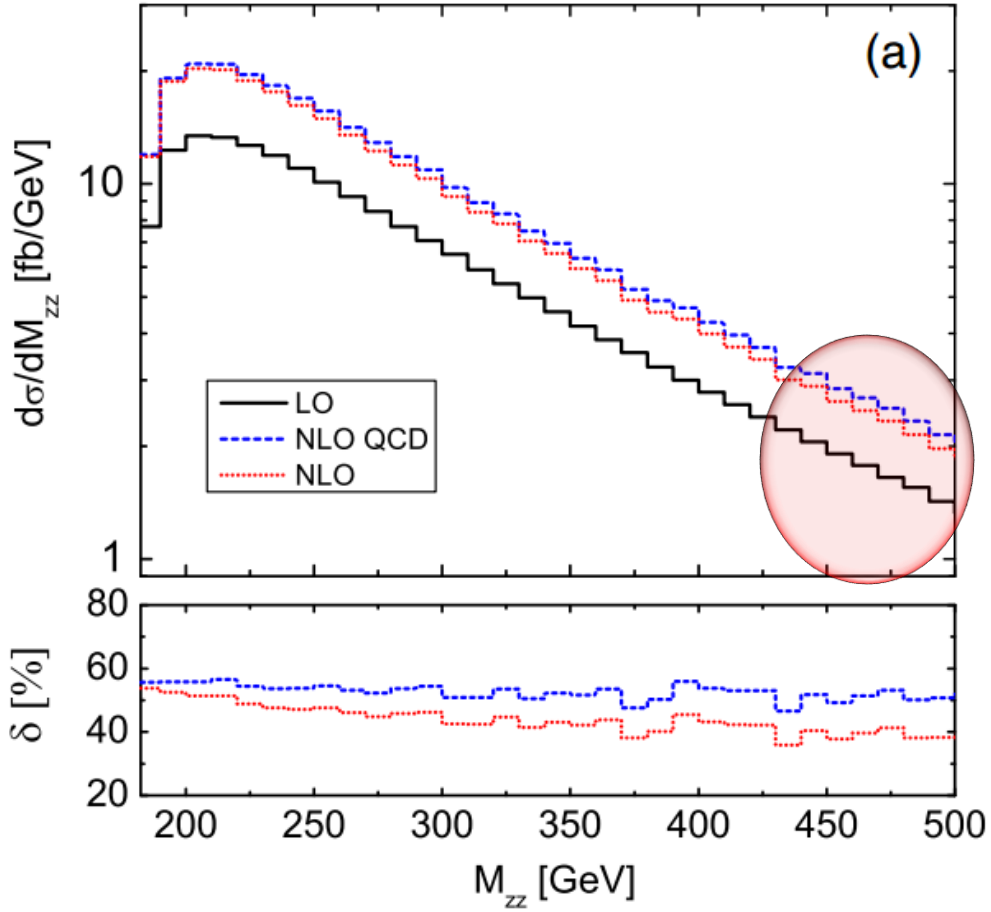
$\sqrt{S}$ [TeV]	σ^{LO} [pb]	σ^{NLO} [pb]	δ_{QCD} [%]	δ_{EW} [%]	$\delta_{\gamma\text{-ind}}$ [%]	δ_{NLO} [%]
13	1.8709(1)	2.708(4)	52.6	−5.22	0.13	44.76
14	2.1348(3)	3.087(5)	52.6	−5.32	0.13	44.61
33	8.6670(8)	12.63(2)	54.4	−5.66	0.10	45.76
100	41.916(5)	60.45(8)	53.5	−6.10	0.07	44.21

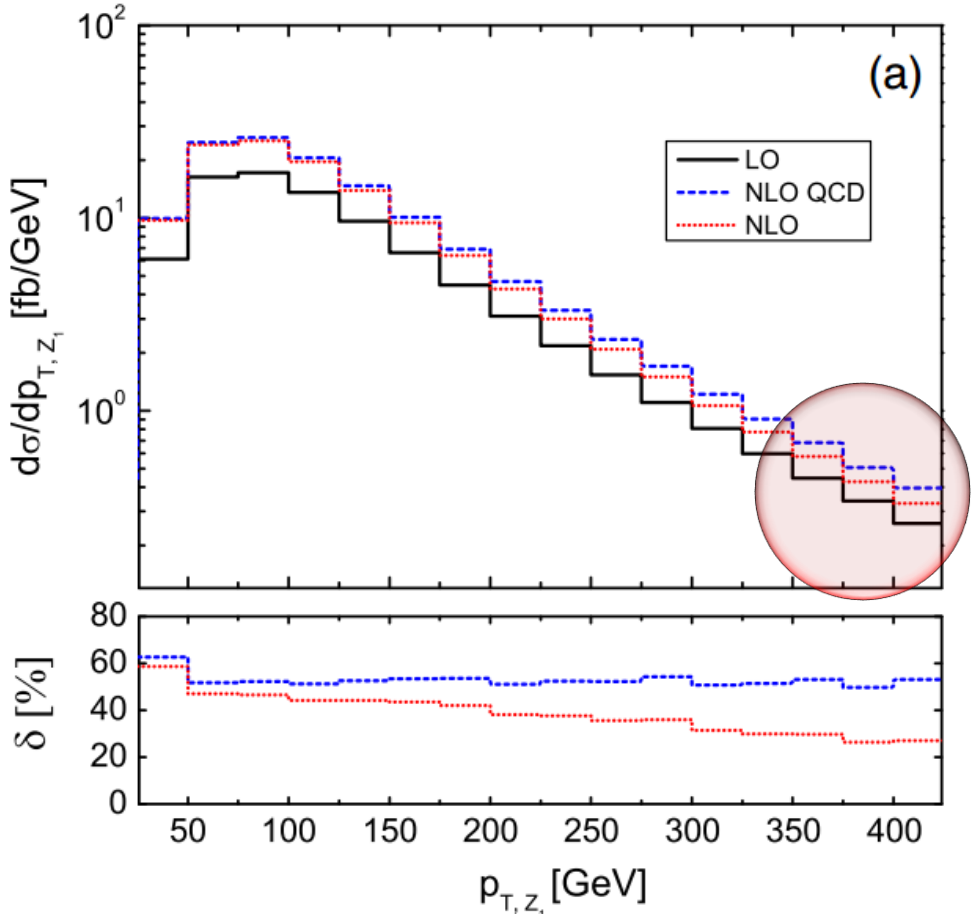
$p_{T,\text{jet}}^{\text{cut}}$ [GeV]	σ^{LO} [pb]	σ^{NLO} [pb]	δ_{QCD} [%]	δ_{EW} [%]	$\delta_{\gamma\text{-ind}}$ [%]	δ_{NLO} [%]
20	5.2701(6)	7.146(9)	42.0	−4.59	0.11	35.59
50	2.1348(3)	3.087(5)	52.6	−5.32	0.13	44.61
100	0.76528(7)	1.176(2)	65.2	−7.04	0.16	53.73
200	0.16125(2)	0.2759(4)	91.8	−10.91	0.20	71.07

Typically 1/10 δ_{QCD} suppression on integrated LO CS.

Phenomenological negligible due the small photon PDF.

III. Numerical results-$pp \to ZZ + jet$





A significant suppression due to EW Sudakov logarithms can be observed !

III. Z–boson decays $pp \to \cdots \to 4l + jet$

- **Simplest**: Naïve-NWA method → very fast but inaccurate !
- **Intricate**: Computing stable particle produced amplitudes → accurate but costly !

Intermediate solutions (MadSpin based on FLMW approach):

--P. Artoisenet et al. JHEP 03 015(2013) & S.Frixione et al JHEP 04 081(2007)

a) Generate the NLO events for the undecayed production.
b) Construct the virtualities of resonances and momentum reshuffling. reserve off-shell effects
c) Generate the decay of resonance uniformly. narrow width approximation
d) **Unweighting procedure** *rejection or acceptance condition*

$$\frac{d\sigma}{d\mathbf{x}d\mathbf{y}}(X_{\rm dk}(\mathbf{x},\mathbf{y})) > rW_{\rm max}(X)$$

$$W_{\rm max}(X) = \frac{d\sigma_{\text{no-dk}}}{d\mathbf{x}}(X) \times W^{\rm dk}$$

Decayed events with kinematics $X_{\rm dk}(\mathrm{x},\mathrm{y})$

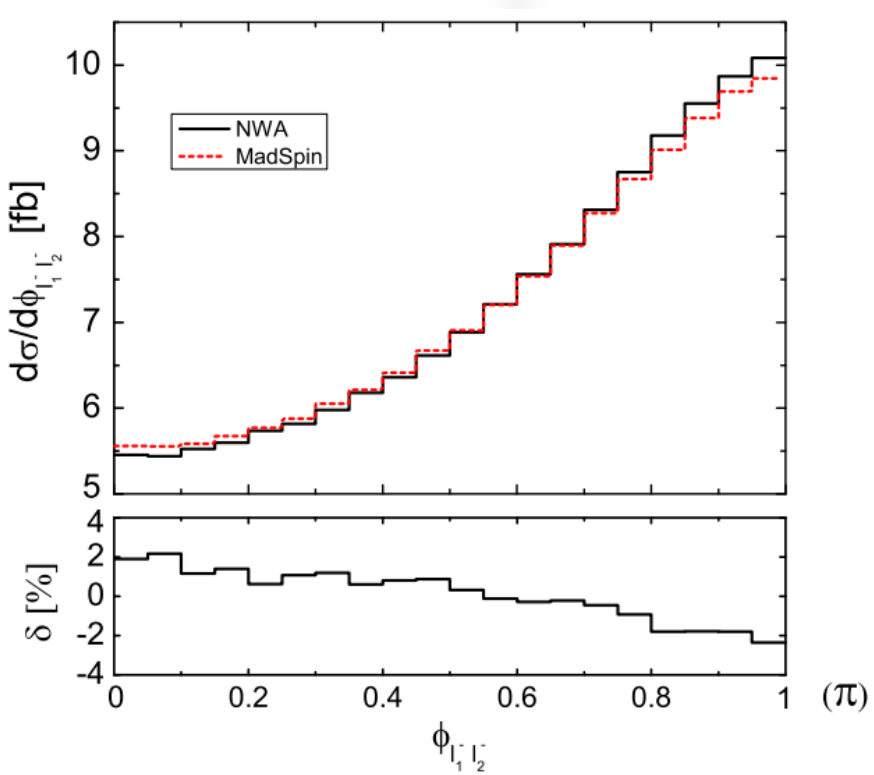
A random number r ∈ [0,1]

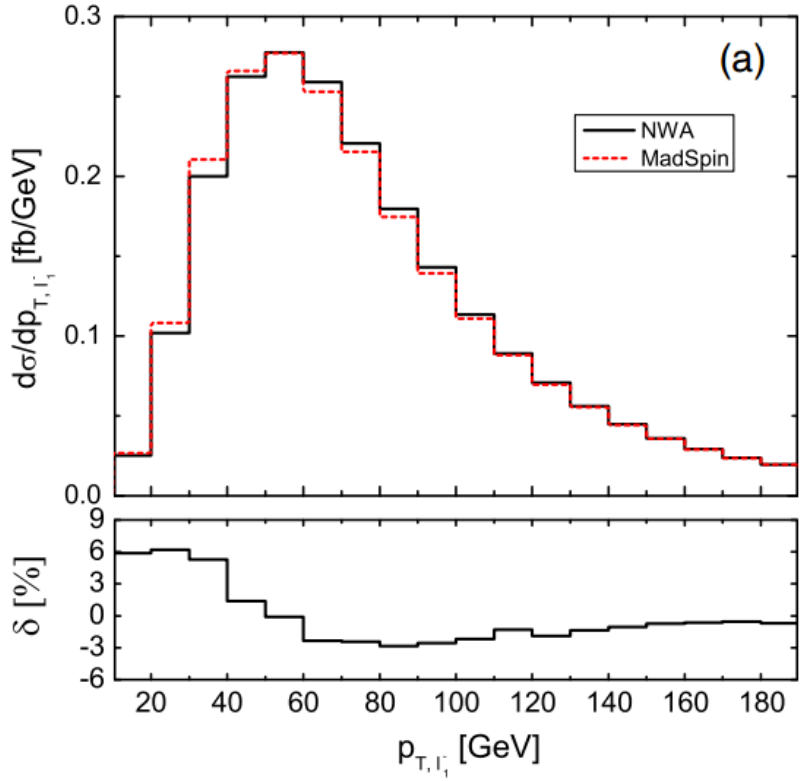
Spin correlation and off-shell effects are reserved at tree-level accuracy !

III. Numerical results $pp \to \cdots \to 4l + jet$

Retain the spin-correlation and off-shell effects fairly well at NLO calculation !

The **MadSpin** is used to decay resonance rather than **naïve-NWA** !





Using MadSpin in NLO calculations could be a better choice !

Distributions of Z-boson leptonic decays

III. Numerical results-$pp \to ZZ + \gamma$

$\sqrt{s} = 14$ TeV	Frixione isolation		fragmentation function	
	inclusive	exclusive	inclusive	exclusive
$\sigma^{LO}/[\text{fb}]$	$23.816(3)^{+2.95\%}_{-3.72\%}$			
$\delta_{EW}/[\%]$	-6.76			
$\delta_{\gamma\text{-ind}}/[\%]$	0.02	0.004	0.02	0.002
$\delta_{QCD}/[\%]$	67.4	52.6	63.9	48.6
$\delta_{NLO}/[\%]$	56.11	42.29	52.85	38.56
$\sigma^{NLO}/[\text{fb}]$	$37.18(4)^{+2.41\%}_{-1.89\%}$	$33.89(4)^{+1.48\%}_{-1.31\%}$	$36.40(2)^{+3.07\%}_{-1.75\%}$	$33.00(2)^{+1.16\%}_{-1.37\%}$

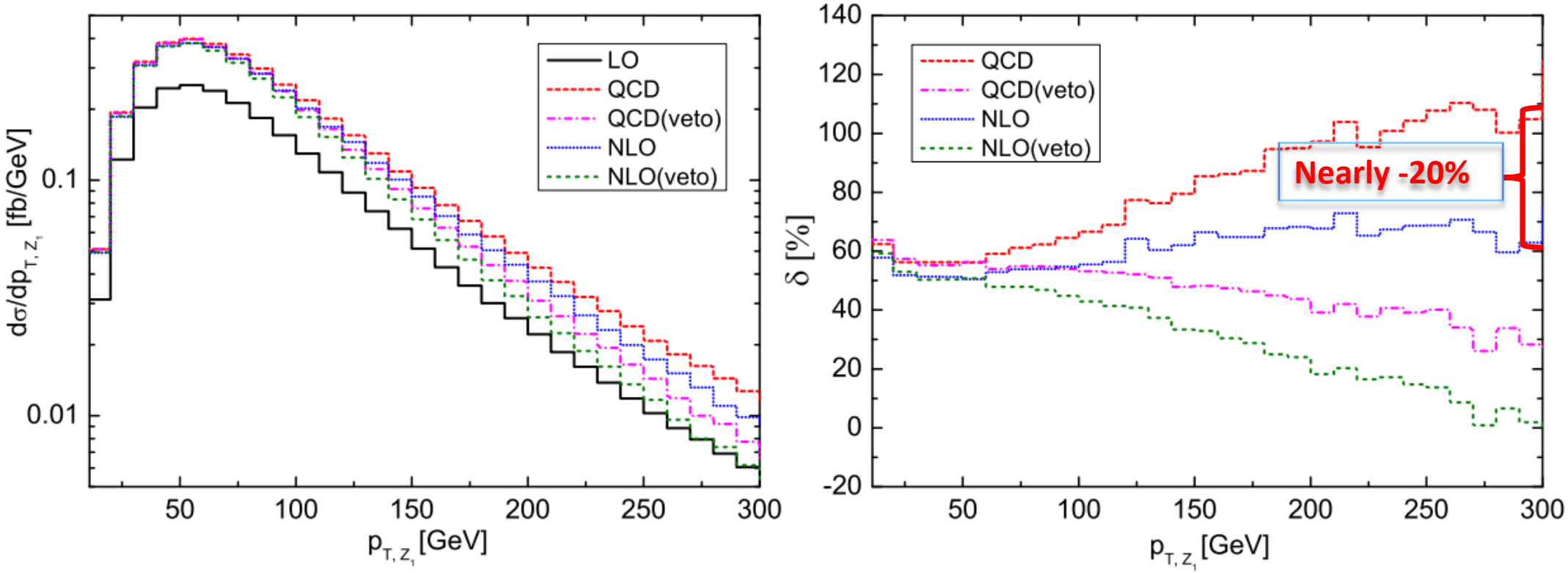
Numerical comparable with QCD corrections !

Phenomenological negligible !

Table 1: The LO, NLO QCD+EW corrected integrated cross sections and the corresponding relative corrections at the 14 TeV LHC by taking $p_{T,\gamma}^{cut} > 20$ GeV, $|y_\gamma| < 2.5$. The results are given in two photon-jet separation methods (see section 2.3.3) by applying the jet veto condition $p_{T,jet}^{cut} < 100$ GeV as well as without it.

Reduce scale dependence ! (further by jet veto)

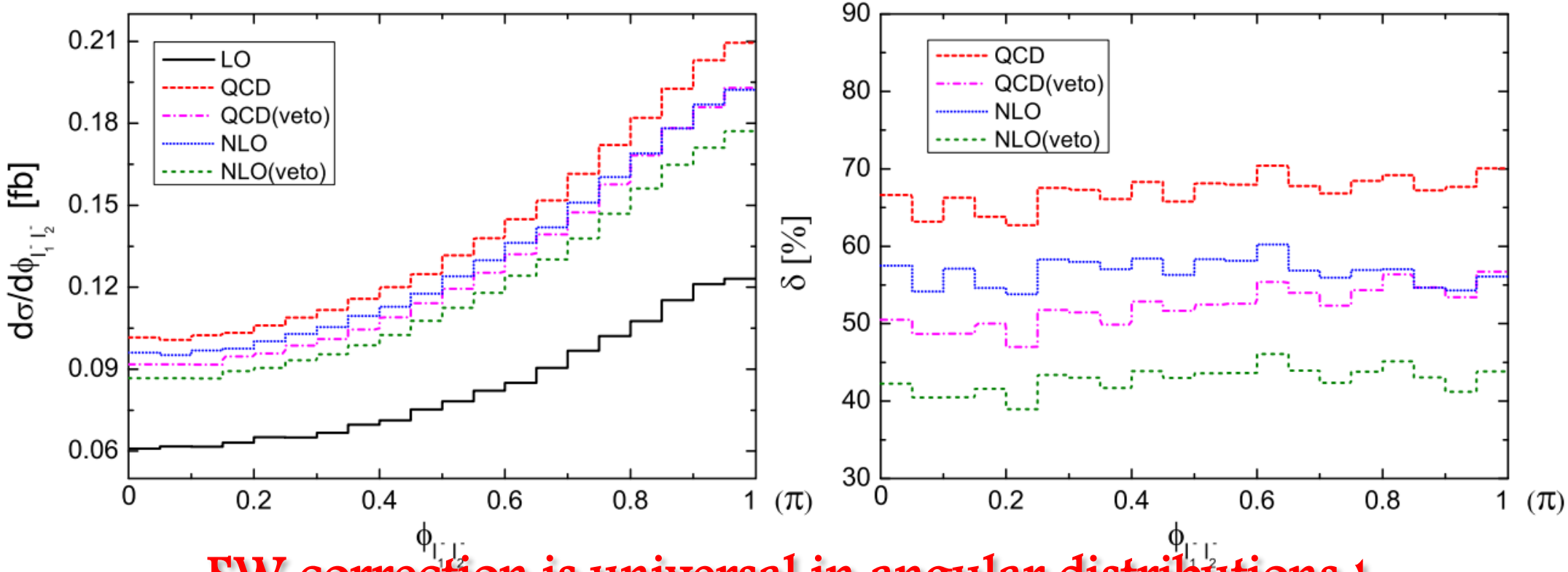
III. Numerical results-$pp \to ZZ + \gamma$



EW correction is significant in the high energy region !

Figure 6: The distributions in the leading Z-boson transverse momentum at LO, NLO QCD and NLO QCD+EW accuracy for $pp \to ZZ + \gamma + X$ at the 14 TeV LHC (left). The relative corrections for corresponding NLO QCD and NLO QCD+EW are also present (right).

III. Numerical results-$pp \to ZZ + \gamma$



EW correction is universal in angular distributions !

Figure 13: The distributions in the leading and next-to-leading negatively lepton transverse momentum (upper box) and relative deviation (lower box) for $pp \to ZZ + \gamma \to 4\ell + \gamma + X$ at the 14 TeV LHC.

IV. Summary

- We completed the first NLO QCD+EW corrections for $\boldsymbol{ZZ + jet}$ and $\boldsymbol{ZZ + \gamma}$ productions at LHC.
- The jet-photon separation is proper coped the with quark-to-photon fragmentation and Frixione isolation.
- EW corrections relative small in the integrated cross section, but non-negligible especially in high energy region.
- The spin correlation and off-shell effects are partially retained by using MadSpin.

Thank You !