

NLO QCD corrections to $VVjj$ production at the LHC

Physics at LHC and beyond

Francisco Campanario, Matthias Kerner, LE Duc Ninh, Dieter Zeppenfeld | August 11 2014



- $VVjj$ production (with leptonic decays) at the LHC: motivation
- $VVjj$ @ NLO QCD : some calculational details
- Phenomenological results: WZ , $W\gamma$, ZZ , $Z\gamma$ (NEW), W^+W^+
- Summary

$VVjj$ production at the LHC: why?

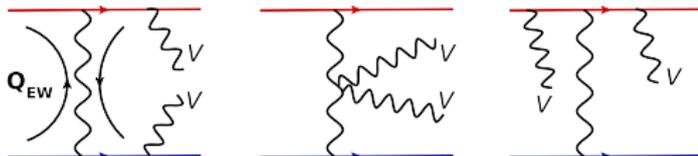
- Motivation:
 - Sensitive to $VV \rightarrow VV$ scattering, quartic gauge-boson couplings.
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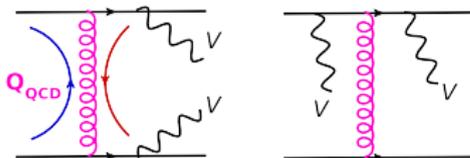
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- Important background for new physics searches.

- Classification at LO: 2 mechanisms

- EW mechanism (vector boson fusion, VBF): $\sigma_{EW} \propto \alpha^6$

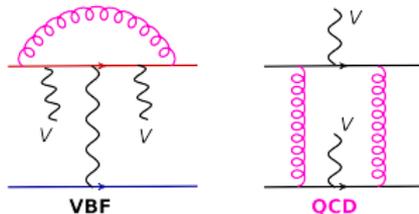


- QCD mechanism: $\sigma_{QCD} \propto \alpha_s^2 \alpha^4$



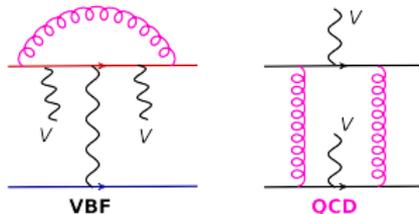
- Interference: color and kinematically suppressed.
→ can be neglected for a-few-percent precision measurements at the LHC.

What have been done at NLO QCD?



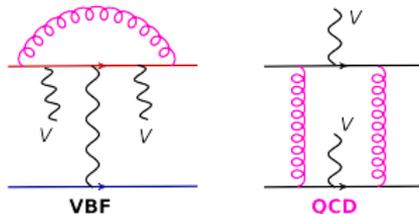
- EW mechanism (VBF): consider QCD corrections to each quark lines separately
↪ pentagons at most.
 - $W^+ W^- jj$: [Jager, Oleari, Zeppenfeld, 2006]
 - $ZZjj$: [Jager, Oleari, Zeppenfeld, 2006]
 - $W^\pm Zjj$: [Bozzi, Jager, Oleari, Zeppenfeld, 2007]
 - $W^\pm W^\pm jj$: [Jager, Oleari, Zeppenfeld, 2009], [Denner, Hosekova, Kallweit, 2012]
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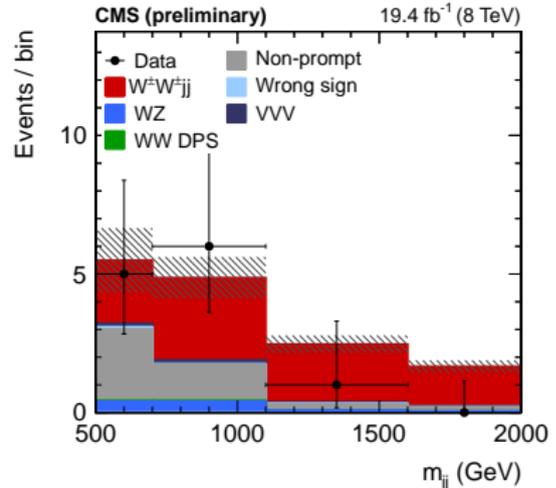
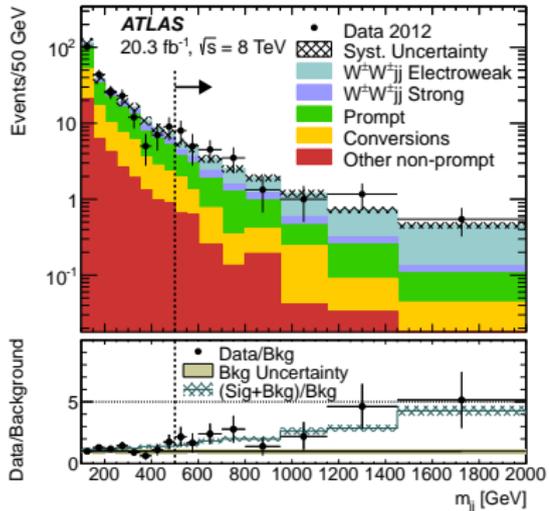
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 - $W^\pm Zjj$, $W^\pm \gamma jj$, $ZZjj$, $Z\gamma jj$: [Campanario, Kerner, LDN, Zeppenfeld, 2013, 2014]

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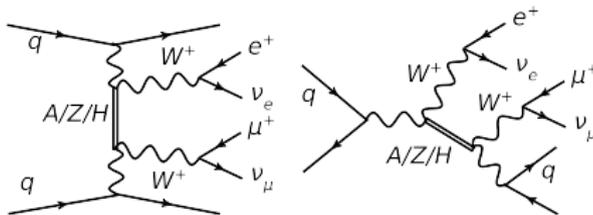
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- almost all processes (notable exception: QCD $W^+ W^- jj$) are included in VBFNLO program.
- Same-sign $W^\pm W^\pm jj$ are special: clean signal, small background (no $t\bar{t}$), simplest calculation.

Same-sign $W^\pm W^\pm jj$ @ATLAS & CMS, 2014

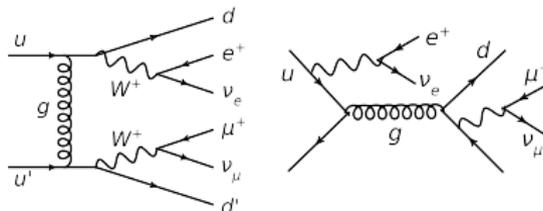


See, we can already do something at 8TeV!

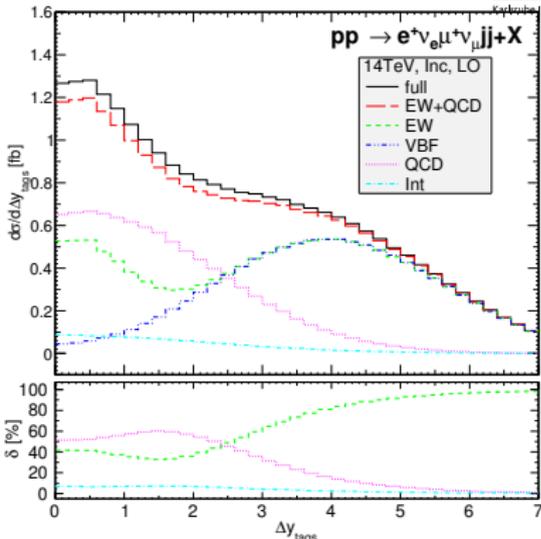
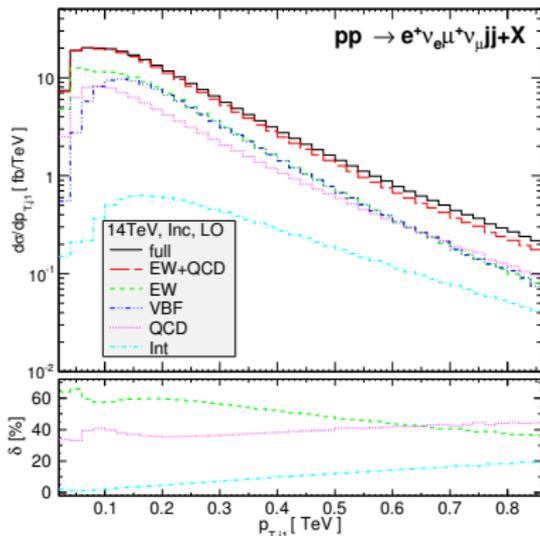
- EW: $\sigma_{EW} \propto \alpha^6$



- QCD: $\sigma_{QCD} \propto \alpha_s^2 \alpha^4$



- Interference: $\sigma_{Int} \propto \alpha_s \alpha^5$, maximal for same-sign $W^\pm W^\pm jj$ due to the absence of gluon-induced processes and only left chiral quarks and leptons involve.



$$p_{T,j} > 20 \text{ GeV}, \quad |\eta_j| < 4.5, \quad R_{jj}^{anti-k_t} = 0.4, \quad R_{jj} > 0.4;$$

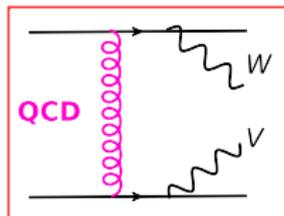
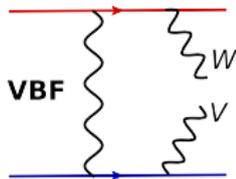
$$p_{T,l} > 20 \text{ GeV}, \quad |\eta_l| < 2.5, \quad R_{ll} > 0.4, \quad \not{p}_T > 30 \text{ GeV}.$$

Dynamic scale: $\mu_F = \mu_R = \mu_0 = \left(\sum_{\text{partons}} p_{T,i} + \sum_i \sqrt{p_{T,W_i}^2 + m_{W_i}^2} \right) / 2$,

$p_{T,W}$ (m_W) are reconstructed from leptons.

Interference effects: $\leq 15\%$ in relevant phase space region.

$pp \rightarrow VVjj$: QCD mechanism at NLO QCD



- LO: 4840 [$WZjj$, two generations]
- NLO real emission: 79784 [$WZjjj$, two generations]
- NLO virtual: 116896 (up to 6-point rank 5) [$WZjj$, two generations]
- Many subprocesses: most complicated $ZZjjj$ (real emission) has 275 subprocesses (with b quarks)

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Our calculations are efficient and reliable (Facts):

- good classifications: effective currents $V \rightarrow l_1 l_2$, $V \rightarrow l_1 l_2 l_3 l_4$, building blocks (hexlines, penlines, ...), ...
- two independent calculations (Fact: manual calculations are buggy):
 - manual implementation using VBFNLO framework
 - more automated approach using HELAS/MadGraph, FeynArts, FormCalc
 - loop integrals: 2 different codes, in-house LoopInts and VBFNLO implementation.

With an Intel i5-3470 computer with one core and using the compiler Intel-ifort version 12.1.0, to get a statistical error of 1%:

- $W^+ W^+ jj$: 30 minutes.
- $W^+ Zjj$: 2.5 hours.
- $W^+ \gamma jj$: 3 hours. Importance: two integrals in two different regions on-shell $W^+ \rightarrow l^+ \nu_l$ and on-shell $W^+ \rightarrow l^+ \nu_l \gamma$. Two different Breit-Wigner mappings.
- $ZZjj$: 3.5 hours.
- $Z\gamma jj$: 4 hours.

- partons \rightarrow jets: anti- k_t algorithm with a cone radius of $R = 0.4$.
- cuts:

$$p_{T,j} > 20 \text{ GeV}, \quad |y_j| < 4.5, \quad R_{jj}^{\text{anti-}k_t} = 0.4, \quad R_{j\ell} > 0.4;$$

$$p_{T,l} > 20 \text{ GeV}, \quad |y_l| < 2.5, \quad R_{ll} > 0.4, \quad M_{l+l-} > 15 \text{ GeV};$$

$$p_{T,\gamma} > 30 \text{ GeV}, \quad |y_\gamma| < 2.5, \quad R_{l\gamma} > 0.4, \quad R_{j\gamma} > 0.7, \quad \cancel{p}_T > 30 \text{ GeV}.$$

- Final-state real photon: Frixione smooth cone isolation cut. Events are accepted if

$$\sum_{i \in \text{partons}} p_{T,i} \theta(R - R_{\gamma i}) \leq p_{T,\gamma} \frac{1 - \cos R}{1 - \cos \delta_0} \quad \forall R < \delta_0$$

with $\delta_0 = 0.7 \rightsquigarrow$ events with a soft gluon are accepted (IR safety).

$$\mu_{\text{HT}} = \left(\sum_{\text{partons}} p_{T,i} + \sum_{i=1}^2 E_{T,V_i} \right) / 2 \quad (1)$$

$$\mu'_{\text{HT}} = \left(\sum_{\text{jet}} p_{T,i} e^{|y_i - y_{12}|} + \sum_{i=1}^2 E_{T,V_i} \right) / 2 \quad (2)$$

$$\mu_{\text{ET}} = [E_T(jj) + E_T(VV)] / 2 \quad (3)$$

with $y_{12} = (y_1 + y_2)/2$ and $E_T(jj) = (m_{jj}^2 + p_{jj}^2)^{1/2}$, and

$$m_{jj}^2 \approx 2p_{T,i_1} p_{T,i_2} [\cosh(\Delta y_{jj}) - \cos(\Delta \phi_{jj})]$$

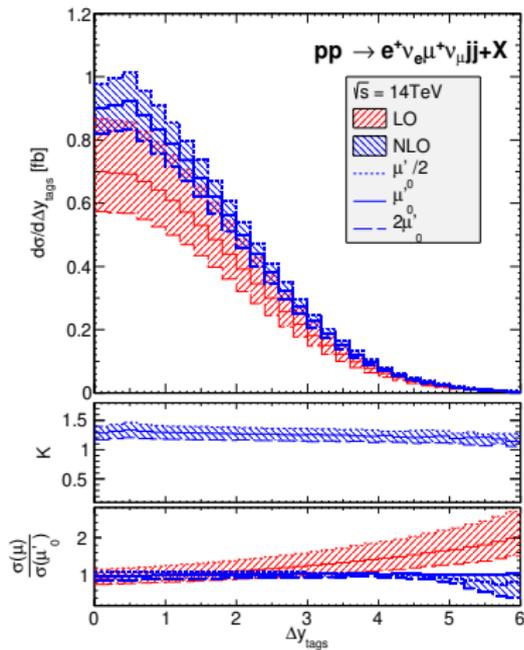
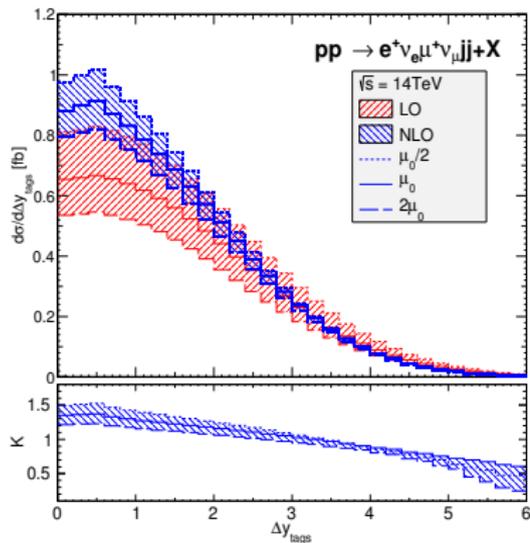
Remarks:

- For large Δy_{jj} , then $\sum p_T \ll m_{jj} \rightsquigarrow \mu_{\text{HT}}$ too small.
- μ'_{HT} and μ_{ET} interpolate between $\sum p_T$ and m_{jj} , for small and large Δy_{jj} , respectively.

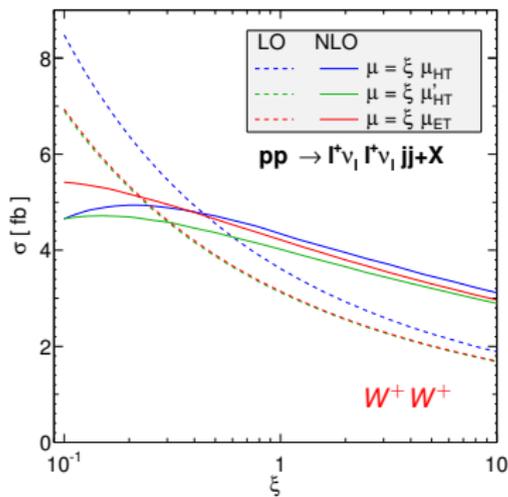
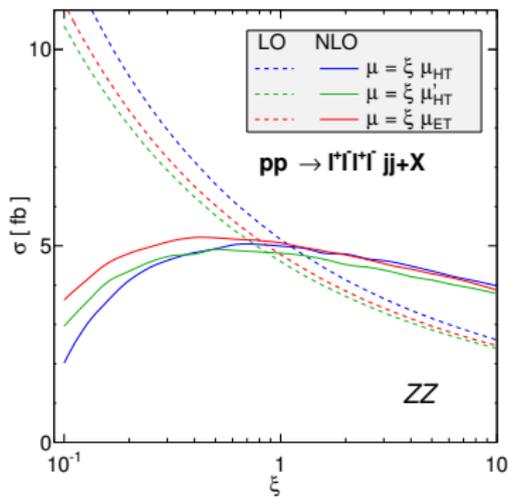
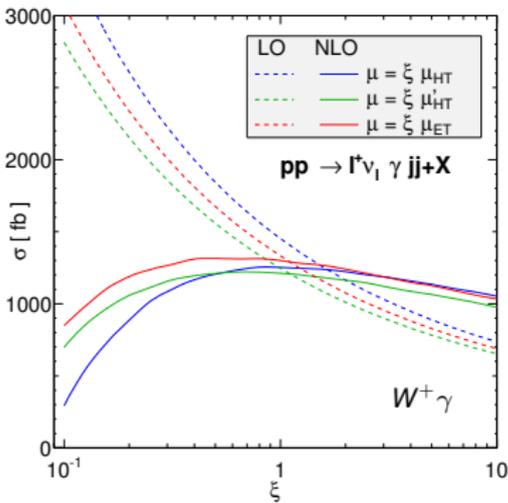
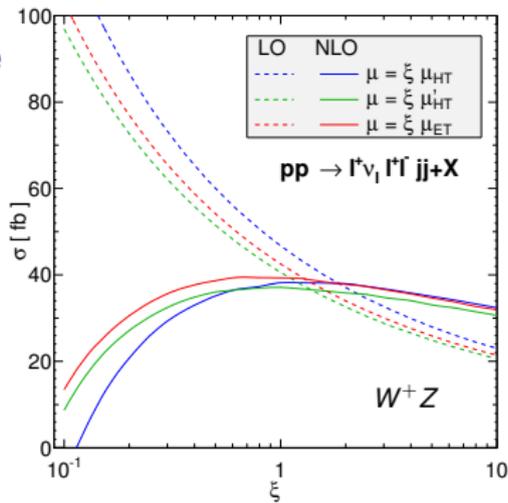
Δy_{jj} distribution: scale choice

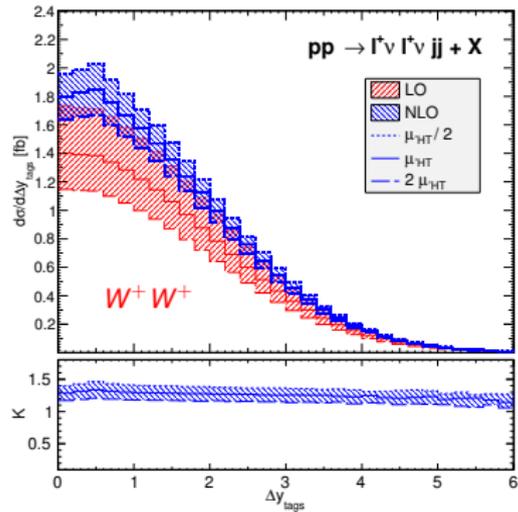
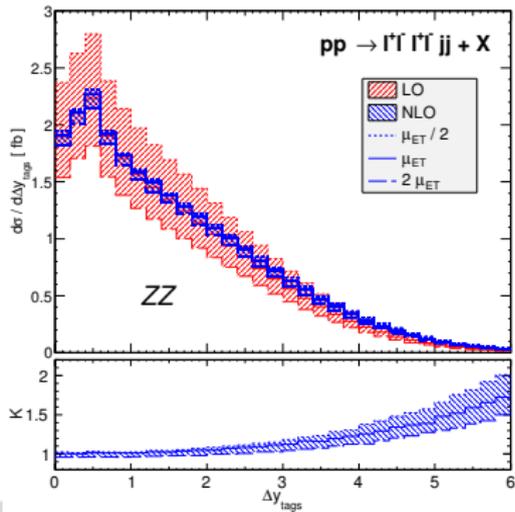
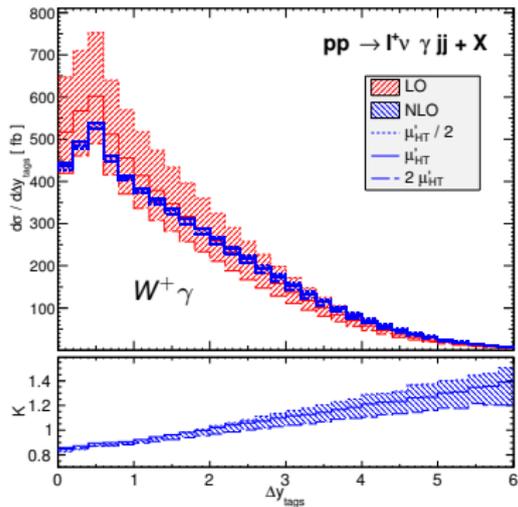
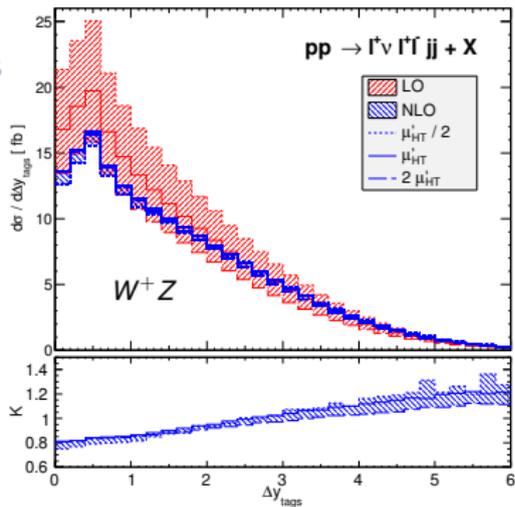
$$\mu_0 = \left(\sum_{\text{partons}} p_{T,i} + \sum_i E_{T,W_i} \right) / 2;$$

$$\mu'_0 = \left(\sum_{\text{jets}} p_{T,i} e^{|\gamma_i - \gamma_{j2}|} + \sum_i E_{T,W_i} \right) / 2$$

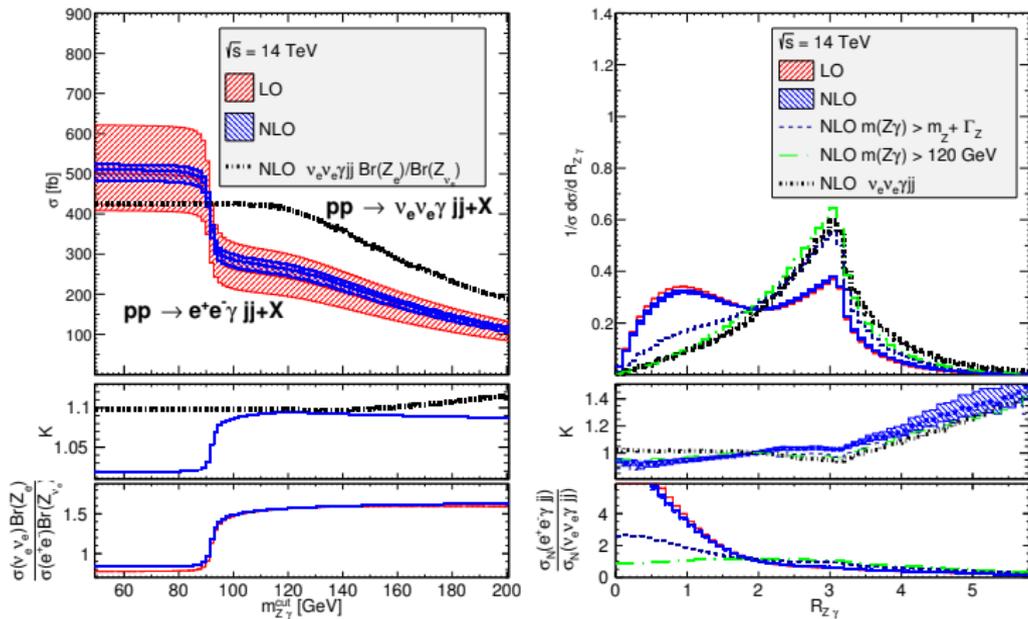


Scale dependence





$Z\gamma jj$: removing $l \rightarrow l\gamma$ contribution



- Key: compare to $\bar{\nu}_e \nu_e e \gamma jj$ channel
- \rightsquigarrow optimal cut: $m(Z\gamma) > 120$ GeV.

- $VVjj$ is a special class of processes: sensitive to $VV \rightarrow VV$ scatterings, quartic gauge couplings, background for new physics searches, ...
- Two mechanisms: EW (VBF), QCD, interference effects are small (at most 15% for W^+W^+jj , expected $\leq 5\%$ for the others).
- NLO QCD corrections for all $VVjj$ are under control.
- A good scale choice has to take m_{jj} into account, p_T alone is not enough.
- The program VBFNLO 2.7.0: includes $WZjj$, $W_\gamma jj$, $W^\pm W^\pm jj$. $ZZjj$, $Z_\gamma jj$ will be in the next release (or upon request).

Thank you!