VVjj and *Hjjj* Production at LHC

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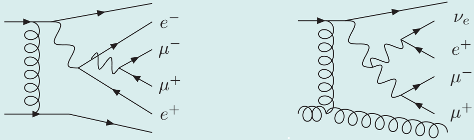
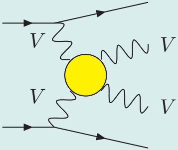
$VVjj$ at LHC

QCD-Induced



VBF Processes



Background:

- VBF
  - $VV \to VV$: EW symmetry breaking in nature
  - Anomalous coupling searches
- Higgs searches ($W^+W^-jj, ZZjj, Z\gamma jj, \gamma\gamma jj$)
- To BSM model searches ($W^\pm W^\pm jj \to l^\pm l^\pm + p_{T,\mathrm{miss}}$)

QCD-induced: known NLO QCD [$WZ, W\gamma, ZZ, Z\gamma, W^\pm W^\pm$ at VBFNLO]
$W^\pm W^\pm jj$ and W^+W^-jj: [T.Melia et al 1007.5313, 1104.2327], W^+W^-jj: [N.Greiner et al.1202.6004]
$\gamma\gamma jj$: [Gehrmann, Greiner, Heinrich, 1308.3660; Badger et al 1312.5927]

NLO Cross-Section

NLO: Real + Virtual contributions:

$$\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

Problem: Both contributions Divergent

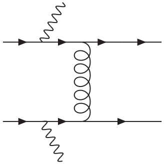
→ Add counter-terms:

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R|_{\epsilon=0} - d\sigma^A|_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

Done a la Catani-Seymour

Two independent Calculations.

$W^\pm W^\pm jj$: Scale Uncertainty



Cuts: anti-kt, $p_{T_{l(j)}} > 20\mathrm{GeV}, \not{p}_T > 30 GeV,$
$|y_{l(j)}| < 2.5(4.5), R_{xy} > 0.4$

Scales:

$\mu_R = \mu_F = \mu_0 =$
$1/2 \left(\sum_{\text{partons}} p_{T,i} + \sum_i \sqrt{p^2_{T,i} + m^2_{W,i}} \right)$

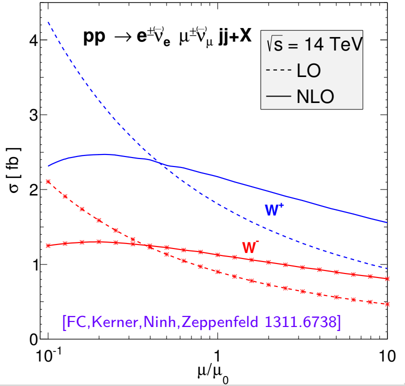
Scale Uncertainty:

LO: 40 %

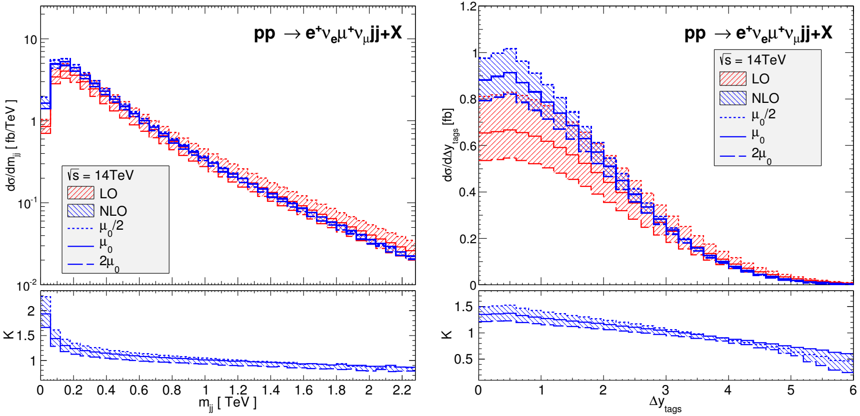
NLO: 10 %

Speed:

1% in 15min in 1 Core at NLO



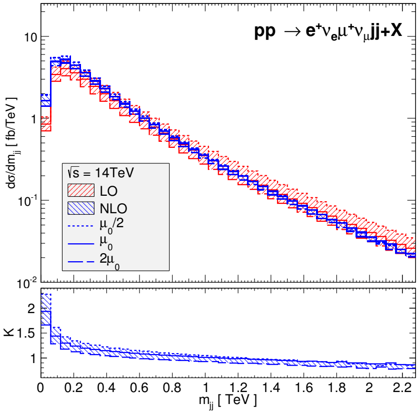
$W^{\pm}W^{\pm}jj$: Jet Distributions

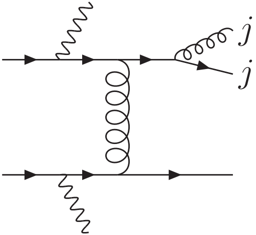


Large corrections up to factor 2

→ Devoted MC programs with flexible cut and distributions

$W^\pm W^\pm jj$: Jet Distributions





Large corrections up to factor 2

→ Devoted MC programs with flexible cut and distributions

$W^{\pm}W^{\pm}jj$: New Scale

- For $\Delta y_{jj} > 3 \rightarrow m_{jj} >> (p_T, H_T)$

$$m_{jj}^2 \approx 2 p_{T,j1} p_{T,j2} (\cosh(\Delta y_{jj}) - \cos(\Delta\phi_{jj}))$$

$$\mu_0' = \frac{1}{2}\left(\sum_{jets} p_{T,i} e^{|y_i - y_{12}|} + \sum_i \sqrt{p_{T,W_i}^2 + m_{W_i}^2}\right)$$

$$\mu_0' \rightarrow \left\{ \begin{array}{l} \sum p_T \\ m_{jj} \end{array} \right. \text{ for } \left\{ \begin{array}{l} \text{small} \\ \text{large} \end{array} \right. \Delta y_{jj}$$

- K-factor flatter
- NLO results within scale uncertainty

Similar scale: $\mu_0'' = \frac{1}{2}\left[E_T(jj) + E_T(VV)\right]$

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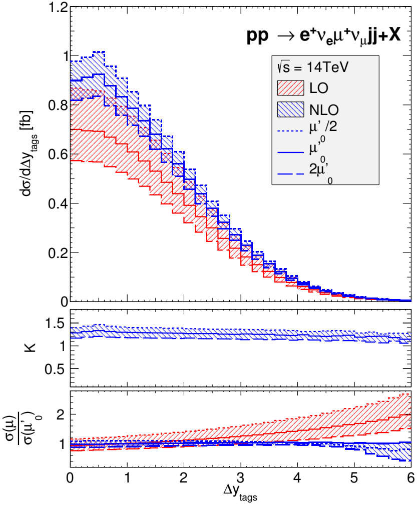

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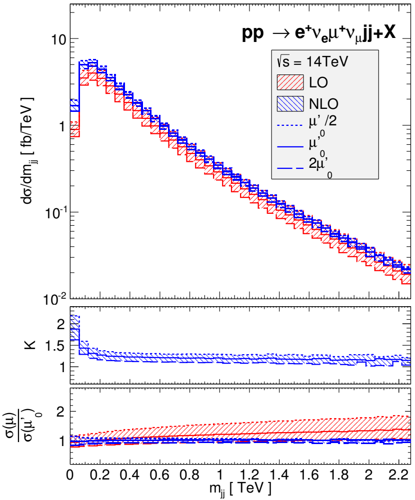

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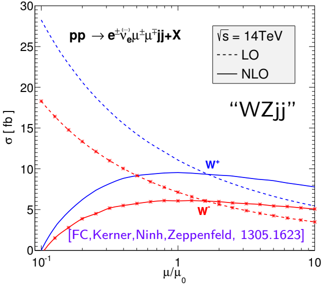
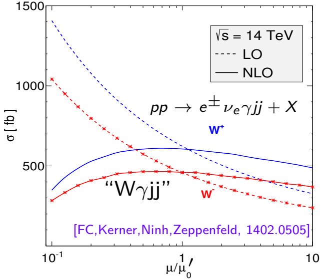
Scale Dependence

Uncertainty: 40% → 10%

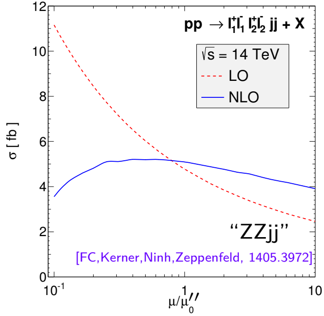


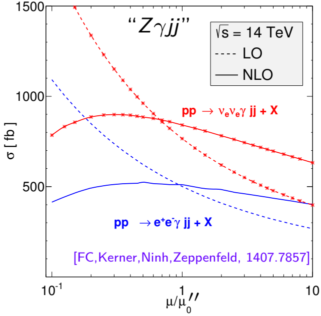


Photon:

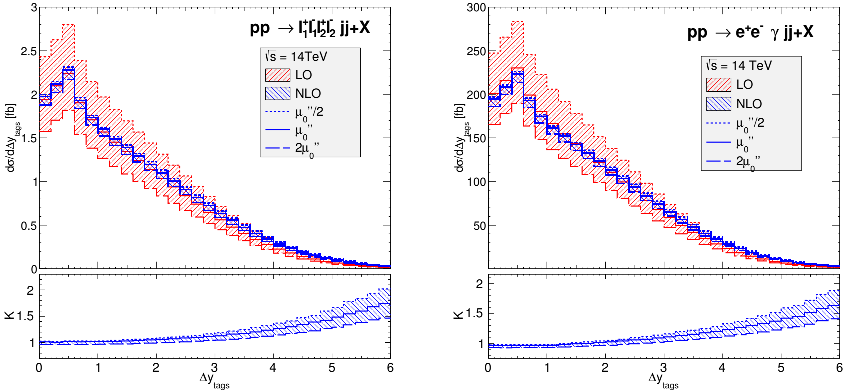
Isolation

a la Frixione

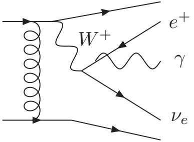


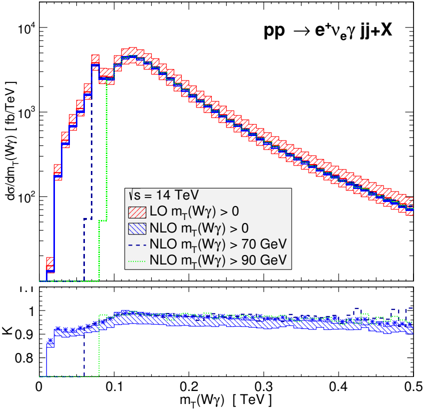


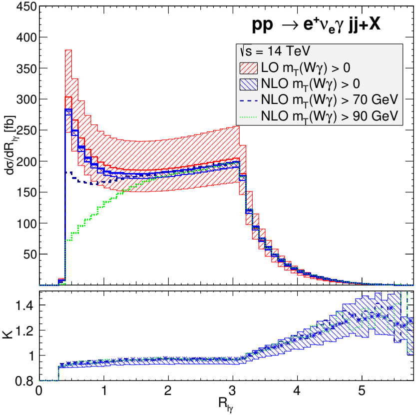
Δy_{tags} Distribution for $ZZjj$ and $Z\gamma jj$



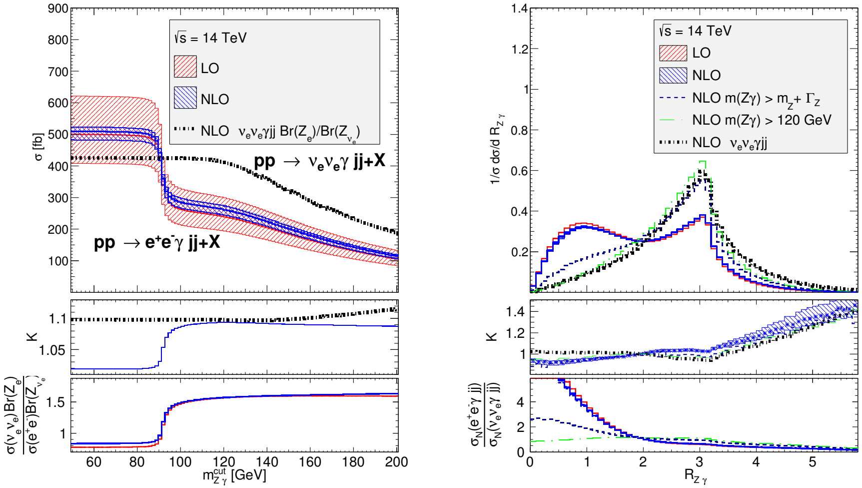
Final State Radiation: $W\gamma jj$



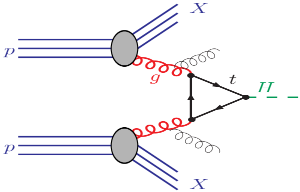


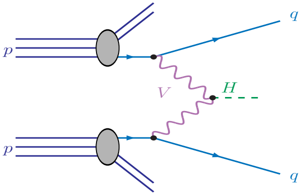


Final State Radiation: $Z\gamma jj$



Higgs + 2(3) jet Production at LHC





GF H+2j:

- Background to WBF
- Sensitive to: CP-structure and coupling of fermions
- LO known for the full Theory [Del Duca et al.hep-ph/0105129;FC,Kubocz,Zeppenfeld 1011.3819]
- NLO known within Effective Theory[Campbell,Ellis,Zanderighi hep-ph/0608194]

GF H+3j:

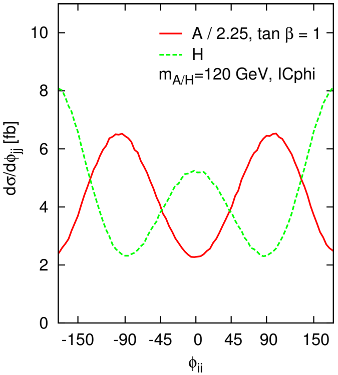
- Background to WBF process[1] (CJV strategies known at NLO)

[1][Figy,Hankele,Zeppenfeld 0710.5621; FC,Figy,Platzer,Sjodahl 1308.2932]

- NLO corrections known within Effective Theory [Cullen et al. 1307.4737]
- Here: LO corrections for the full Theory [FC,Kubocz 1306.1830; 1402.1154]

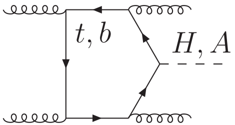
GF Higgs + 2 jet Production at LHC

- sensitive to the $\mathcal{CP}$-structure $\rightarrow$ azimuthal angle correlation



$$\phi_{jj} = \phi_F - \phi_B$$

$$\mathcal{L}_{\text{Yukawa}} = y_q\, \overline{q}\, q\, H + \mathrm{i}\tilde{y}_q \overline{q} \gamma_5\, q\, A$$



"LO": one loop $2 \rightarrow 3$ process of $\mathcal{O}(\alpha_s^4)$

$$Y_q = \frac{m_q}{v}$$

- ∘ bottom-quark: suppressed
- ∘ top-quark: effective theory

CP-Violating Higgs: Φ

available in VBFNLO

$\Phi = H \cos\alpha + A \sin\alpha$

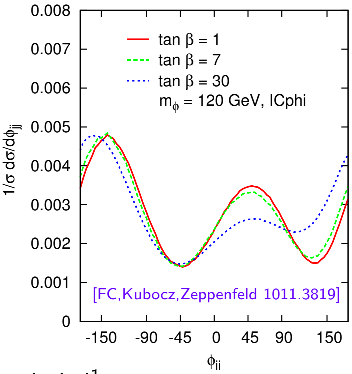
Min: $\tan\Delta\phi_{jj} = -\frac{2y_t}{3\tilde{y}_t}\cot\alpha$

$\circ\ y_q = \tilde{y}_q$ and $\tan\alpha = 2/3$

Min: $\Delta\phi_{jj} = -45^\circ$

Type II HDM(MSSM): $\tilde{y}_b = -\frac{m_b}{v}\tan\beta$

$\rightarrow$ distortion for large $\tan\beta$

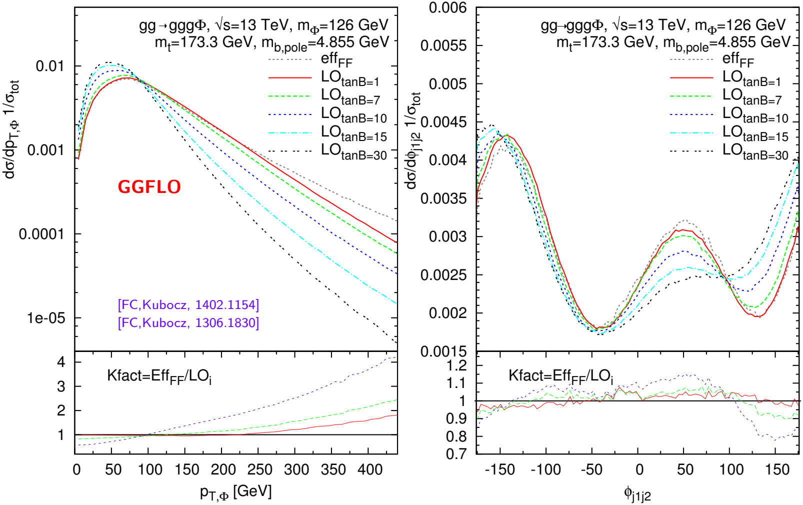


- For 50 fb^{-1} and $\tilde{y}_q = y_q^{SM} \rightarrow \alpha > 40^\circ$ excluded[1]

[1] [Dolan,Harris,Jankowiak,Spannowsky 1406.3322]

- Additional soft radiation?
- Hjjj:First step to an improved NLO Hjj prediction.

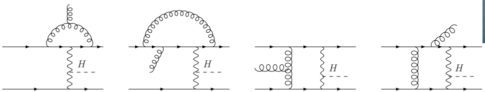
CP-violating Higgs in GF Higgs + 3Jet

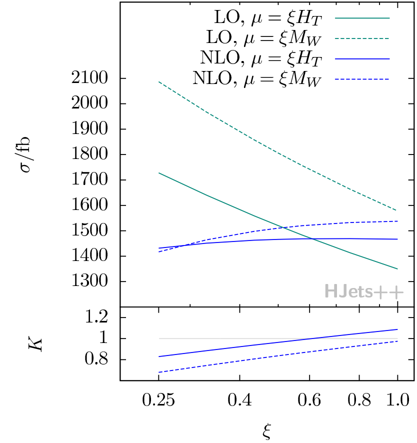


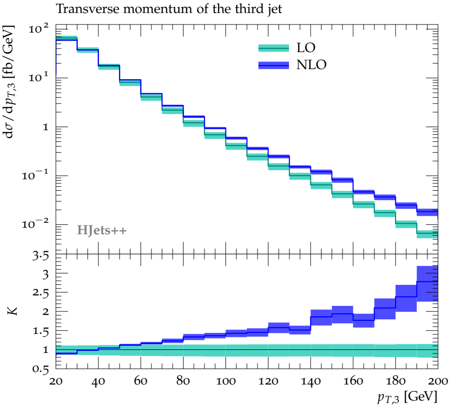
- Bottom corrections important for large $\tan\beta$

VBF *Hjjj* at NLO QCD

[FC,Figy,Platzer,Sjodahl,PRL, ArXiv:1308.2932]







- Vetoed jet in VBF

HJets++: available at http://hjets.hepforge.org

Summary

NLO QCD for the VVJJ processes are known

- Reduction of scale uncertainty
- Corrections phase-space dependent
- Final state radiation efficiently removed by cuts

GF HJJ(J):

- Access to CP-mixing angle and coupling to fermions
- Bottom-loop corrections might distort distributions
- Effective theory: $m_H < m_{top}$ and $p_T^j < m_{\mathrm{top}}$
  - No restriction on m_{jj}. Important for WBF studies.
- Additional soft radiation does not alter sensitive CP-distributions

VBFNLO & GGFLO

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

THANK YOU FOR YOUR ATTENTION