Z+2 jets at NLO in POWHEG

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Outline

- The POWHEG method in a nutshell
- $V + 1$ jet and $V + 2$ jets
- Zjj: details of the implementation
- Results for “signal enhancing” cuts
- Comparison with ATLAS data
- Results for “VBF” cuts
- Conclusions and outlook

NLO vs. SMC's (LO + Parton Shower)

- NLO

✓ NLO accuracy for inclusive observables (not only rates).

✓ reduced theoretical uncertainty (less sensitive to $\mu_{\rm R}$ and $\mu_{\rm F}$ choices).

✗ wrong shapes in small-$p_{\rm T}$ region (or generically where you want to resum logs).

✗ description only at the parton level.

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✗ poor description of high-$p_{\rm T}$ emissions.

✓ Sudakov suppression of small $p_{\rm T}$ emissions (LL resummation, via parton showers).

✓ simulate high-multiplicity events at the hadron level, modelling also NP effects.

✓ largely used by experimental collaborations at various stages.

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natural to try to merge the 2 approaches, keeping the good features of both.

real emissions included in both approaches (and virtual corrections as well)

- NLO: exact $n+1$-body matrix element.
- PS's: multiple emissions in the collinear approximation.

main problem: avoid to double-count them !

many proposals, currently two fully tested solutions: MC@NLO [Frixione, Webber 2001] and POWHEG [Nason 2004].

The POWHEG method

Idea: *Modify* $d\sigma_{\mathrm{SMC}}$ *in such a way that*, expanding in α_{S}, *one recovers the NLO cross section*.

$$B(\Phi_n) \quad \Rightarrow \quad \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$

$$\Delta(t_{\mathrm{m}}, t) \quad \Rightarrow \quad \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)}\theta(k_{\mathrm{T}}' - k_{\mathrm{T}})\, d\Phi_r'\right\}$$

POWHEG "master formula" for the hardest emission:

$$d\sigma_{\mathrm{POW}} = d\Phi_n\ \bar{B}(\Phi_n)\left\{\Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}})\frac{\alpha_s}{2\pi}\frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r\right\}$$

+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting.

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+ $p_{\rm T}$-*vetoing subsequent emissions*, to avoid double-counting.

- Formally it has the same accuracy of MC@NLO:
  inclusive observables @NLO, first hard emission with full tree level ME, (N)LL resummation of collinear/soft logs, extra jets in the shower approximation.
- Main differences:
  - ✓ Events are positive weighted ⇒ POsitive Weight Hardest Emission Generator
  - ✓ Doesn't depend on the parton-shower algorithm used.
    - truncated shower formally needed to restore soft wide-angle radiation effects, when using angular-ordered shower.
      Until now, very small effects observed (for simple processes).

$V+1$ jet

- $\ell\bar{\ell}$ + jets / $\not{E}_T$ + jets: background to BSM searches with two opposite sign leptons or missing E_T involved. W + jets is very relevant for BSM searches too.
- $Z+1$ jet useful for (checking) jet calibration.

Wj and Zj Born matrix elements are singular for $p_{T,j} \to 0$:
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- implemented for Vj, jj and Hj;

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suppression factor

- damp inclusive NLO cross section ($\bar{B}$) when singularities are approached;
- integration is finite;
- weighted events, but easier to have high-p_{T} tails populated;

$$\bar{B}(\Phi_n) \to \bar{B}_{\mathrm{supp}}(\Phi_n) = \bar{B}(\Phi_n)\,\frac{p_{T,V}^2}{p_{T,V}^2+\Lambda^2}$$

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- $\ell\bar{\ell}$ + jets / $\not{E}_T$ + jets: background to BSM searches with two opposite sign leptons or missing E_T involved. W + jets is very relevant for BSM searches too.
- $\tau\tau + 2$ jets: background for Higgs searches (in particular VBF). See later.
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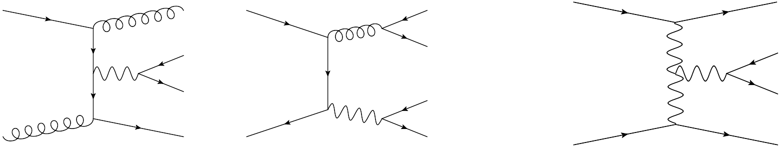
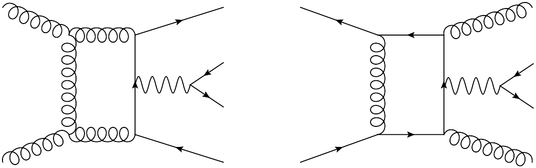
- $Z(\to \ell\bar{\ell})jj$ QCD production ($\mathcal{O}(\alpha_S^2\alpha_{em}^2)$). $Z(\to \ell\bar{\ell})jj$ ($\mathcal{O}(\alpha_{em}^4)$) EW not considered.



- Born amplitudes, B_{ij}, $B^{\mu\nu}$ computed with helicity amplitudes (Hagiwara-Zeppenfeld)
- Real matrix elements obtained with `MadGraph`
- Virtuals computed linking against `BlackHat` (Binoth-LH interface $\Rightarrow$ can be linked with other 1-loop codes)



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- Suppression factor used:

$$\bar{B}(\Phi_n) \to \bar{B}_{\text{supp}}(\Phi_n) = \bar{B}(\Phi_n)\, F(\Phi_n)\,,$$
$$F(\Phi_n) = \left(\frac{p_{T,1}^2}{p_{T,1}^2 + \Lambda_{p_\text{T}}^2}\right)^{k_\text{IS}} \left(\frac{p_{T,2}^2}{p_{T,2}^2 + \Lambda_{p_\text{T}}^2}\right)^{k_\text{IS}} \left(\frac{s_{1,2}}{s_{1,2} + \Lambda_m^2}\right)^{k_\text{FS}}\,,$$
$$k_\text{IS} = k_\text{FS} = 2\,,\;\; \Lambda_{p_\text{T}} = 10\ \text{GeV}\,,\;\; \Lambda_m = 5\ \text{GeV}\,.$$

- similar method used for Hjj in `POWHEG` [Campbell et al., arXiv:1202.5475]
- checked soft/collinear limits with expected values; NLO distributions checked with n-tuples generated with `Blackhat + Sherpa`
- Wjj and $Wjjj$ done with same accuracy, with `aMC@NLO` and `Sherpa-MC@NLO`

  [Frederix et al., arXiv:1110.5502, Hoeche et al., arXiv:1201.5882]

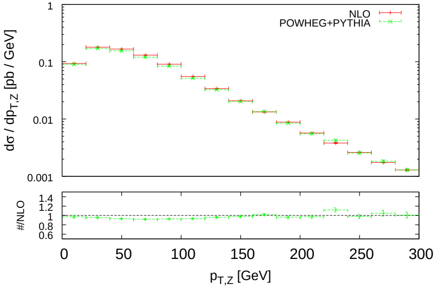
Zjj: "signal cuts"

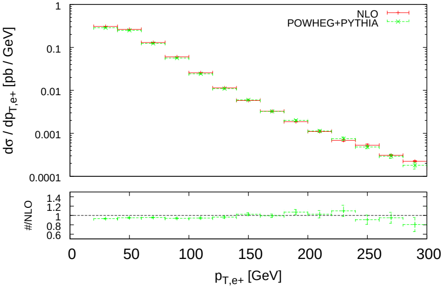
settings:

- PDF: CTEQ6M
- $\mu = \hat{H}_T/2 = \left(\sqrt{m_Z^2 + p_{T,Z}^2} + p_{T,1} + p_{T,2}\right)/2$
- "Perugia 0" tune (PYTHIA6)
- No folding, $\sim 20\%$ neg. weighted events.

cuts:

- $p_{T,e} > 20$ GeV, $|y_e| < 2.5$
- $p_{T,j} > 30$ GeV, $|\eta_j| < 4.4$
- anti-k_T, $R = 0.4$





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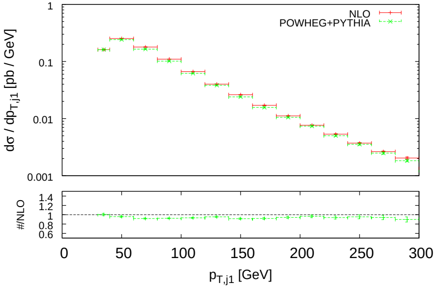

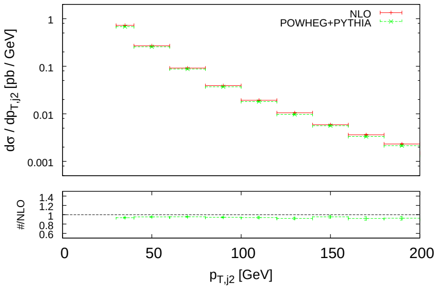

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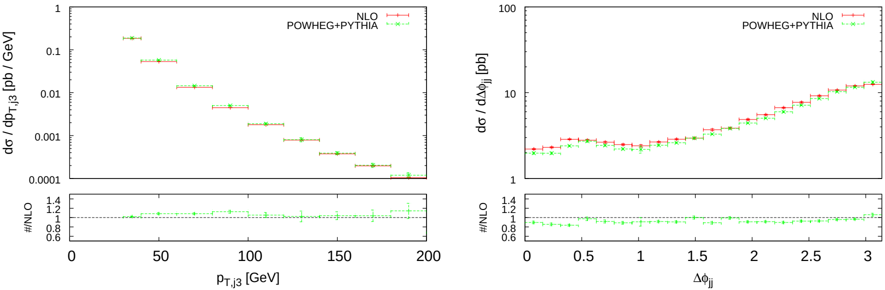

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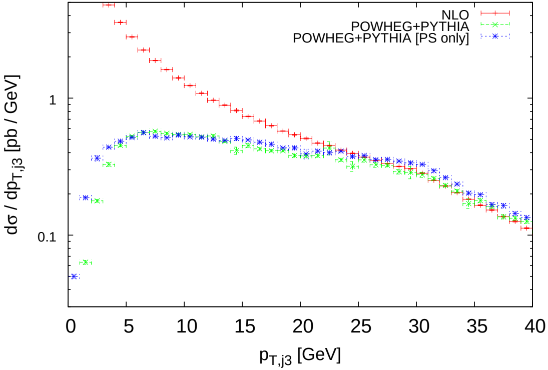
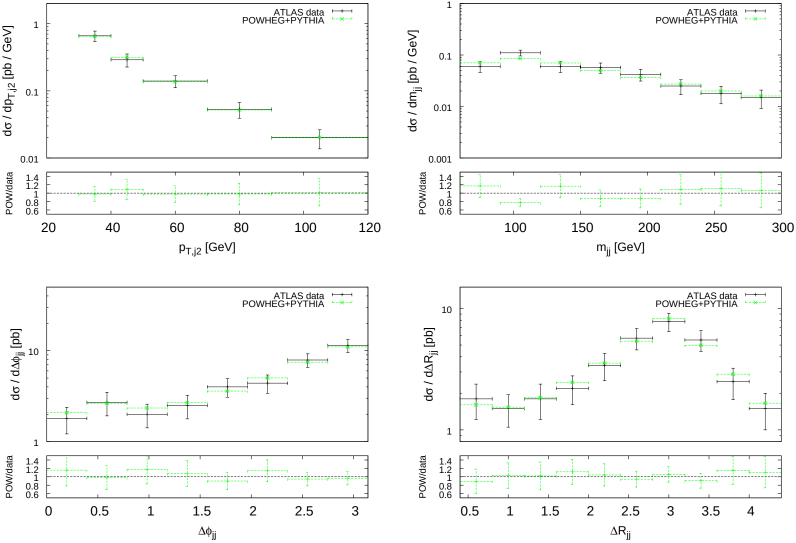


Zjj: comparison with ATLAS data

cuts:

- $p_{T,e} > 20$ GeV, $|y_e| < 2.5$
- $p_{T,j} > 30$ GeV, $|y_j| < 4.4$, $\Delta R_{j,e} > 0.5$
- anti-k_T, $R = 0.4$



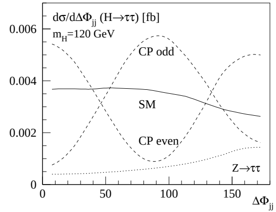
- QCD and EW Zjj are two of the main backgrounds to VBF Higgs, with $H \to \tau\tau$
- $\sigma_{tot}^{EW} \ll \sigma_{tot}^{QCD}$
- Different color structure $\Rightarrow$ different jet activity
- Possible to suppress σ^{QCD} without loosing too much signal
- $\sigma_{VBFcuts}^{QCD} \sim \sigma_{VBFcuts}^{EW}$

Studied QCD Zjj in presence of minimal set of VBF cuts:

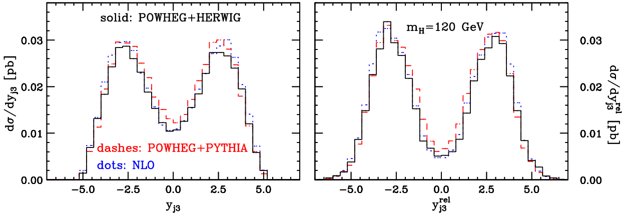
$$p_{T,\ell} > 20\text{ GeV}\,, \quad |y_\ell| < 2.5\,,$$
$$|\eta_j| < 5.0\,, \quad p_{T,j} > 20\text{ GeV}\,, \quad p_{T,j_{\rm tag}} > 30\text{ GeV}\,,$$
$$|\eta_{j_1} - \eta_{j_2}| > 4.0\,, \quad \eta_{j_1} \cdot \eta_{j_2} < 0\,, \quad \text{VBF has forward/backward tagging jets}$$
$$\min(\eta_{j_1}, \eta_{j_2}) + 0.4 < \eta_{\ell^+/\ell^-} < \max(\eta_{j_1}, \eta_{j_2}) - 0.4 \ \text{leptons within the tagging jets.}$$

Further background suppression possible cutting out events with low m_{jj}.

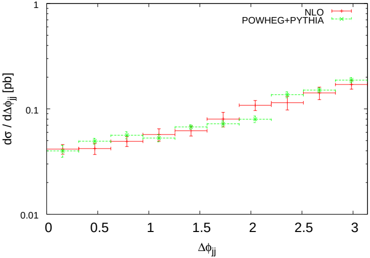
Zjj: "VBF cuts"

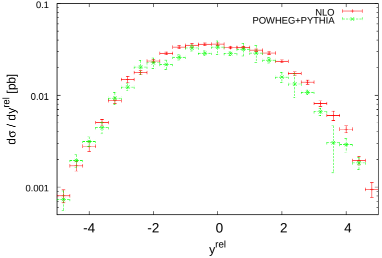


[Plehn,Rainwater,Zeppenfeld, 2001]



[Nason,Oleari, 2009]





- $\Delta\Phi_{jj}$ is known to be useful to study the CP property of the Higgs boson
- $y^{\rm rel} = y_{j_3} - (y_{j_1} + y_{j_2})/2$: distance between 3rd jet and tagging jets (using average jet rapidity)

Conclusions and outlook

- possible to implement complicated processes in `POWHEG`, recently done also for Hjj
- shown good agreement / differences with NLO, as expected
- good agreement with data
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