VV + JETS AND THE POWHEG BOX

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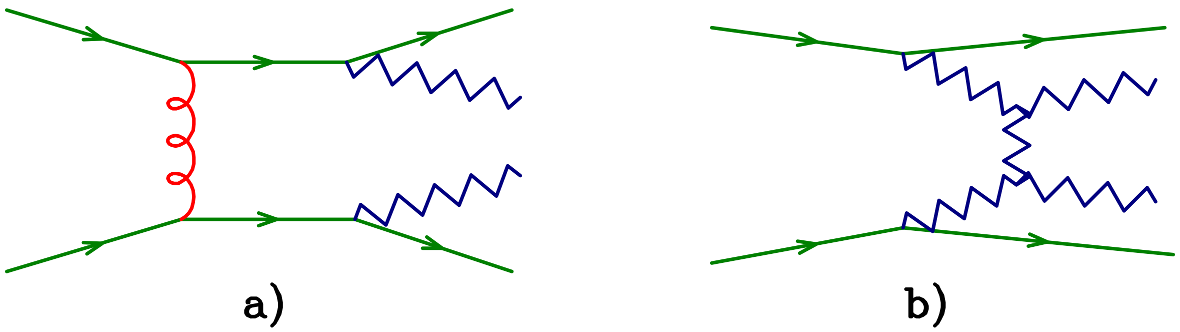
- ✗ The latest VV + jets fixed-order results
- ✗ Vector-boson production in the POWHEG BOX
  - VV production status
  - Recent and less-recent useful features
    - ✓ MiNLO
    - ✓ Generation of QCD and EW radiation
    - ✓ Treatment of resonances
    - ✓ Automatic generation of matrix elements
- ✗ Outlooks and conclusions

VV + jets processes

- "QCD" vector-boson production versus Vector-Boson Fusion/ Scattering (VBF/VBS)
  Only the order of the strong and electromagnetic coupling constants can tell.

  For example, $VV + 2$ jets

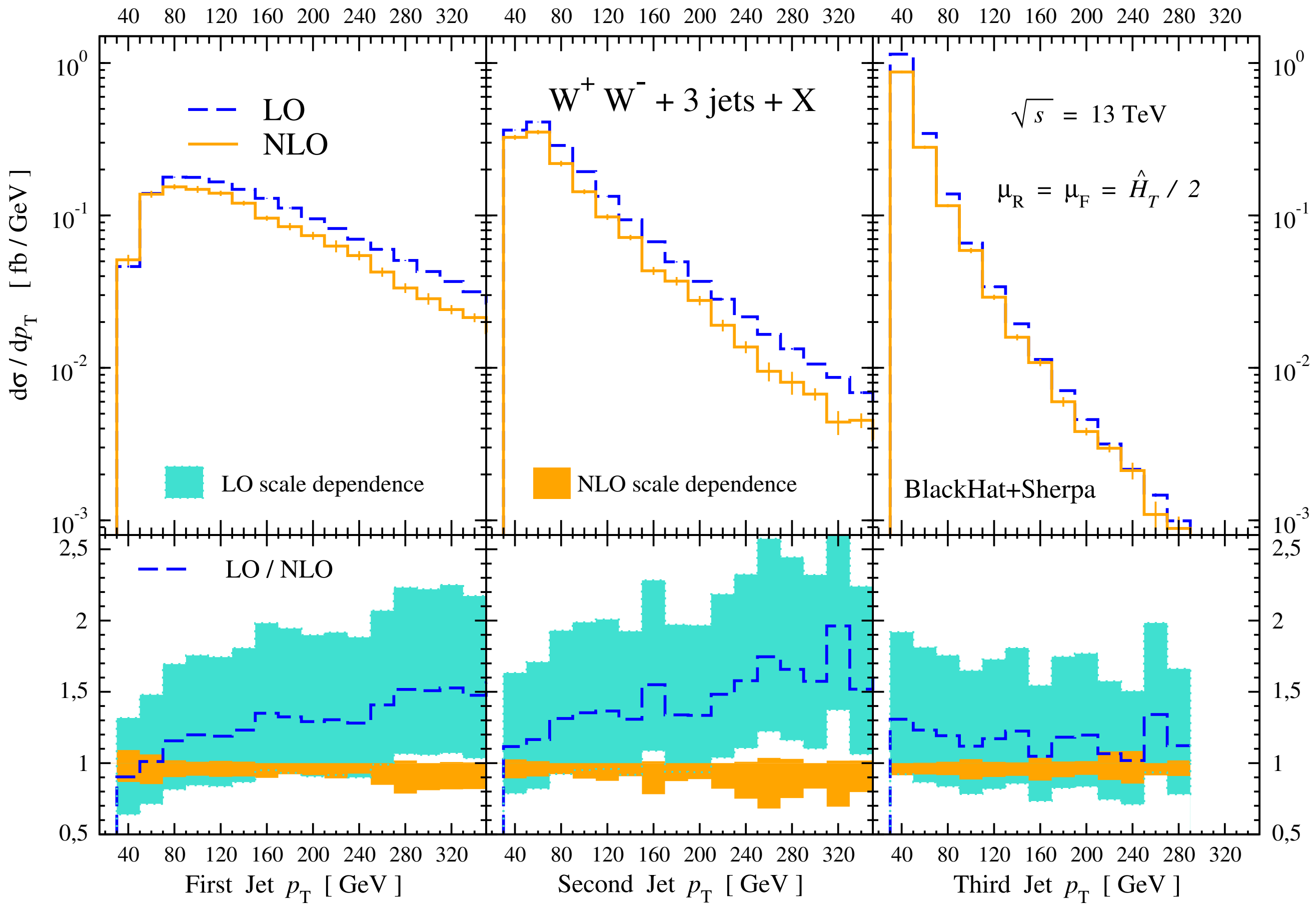


$\mathcal{O}\left(\alpha^2 \alpha_s^2\right)$ $\mathcal{O}\left(\alpha^4\right)$ VBF/VBS

- With or without vector-boson decay? Again, the order of the coupling constants can help.
- If with decay, is it treated exactly? In some approximation?
- Leptonic or hadronic (or both) decay? Important when the virtual loop involves particles from the production and particles from the decay.
- Full leptonic final states or only diagrams with vector bosons in the s channel?
- NLO corrections: QCD? EW? Both?

Fixed-order VV + jets recent results

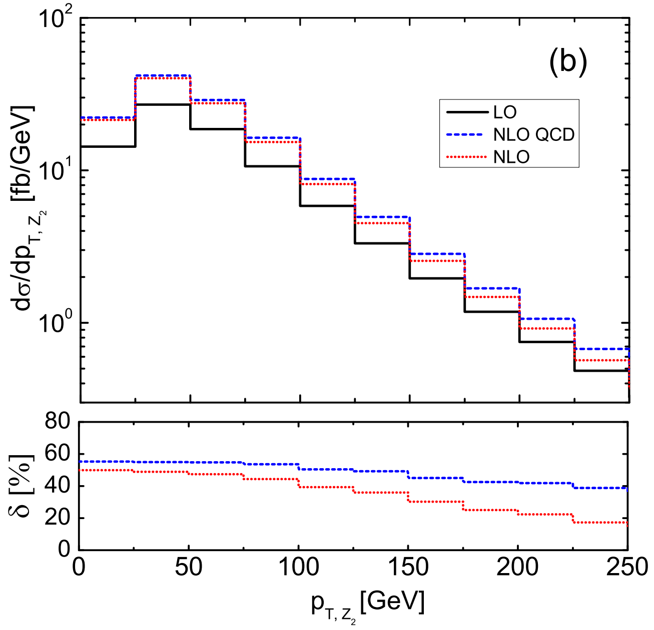
- W^+W^- + 3 jets, $\mathcal{O}\left(\alpha_s^3\alpha^4\right)$, NLO QCD corrections, leptonic W decay considered, (BlackHat and SHERPA) (Febres Cordero, Hofmann, Ita, arXiv:1512.07591)



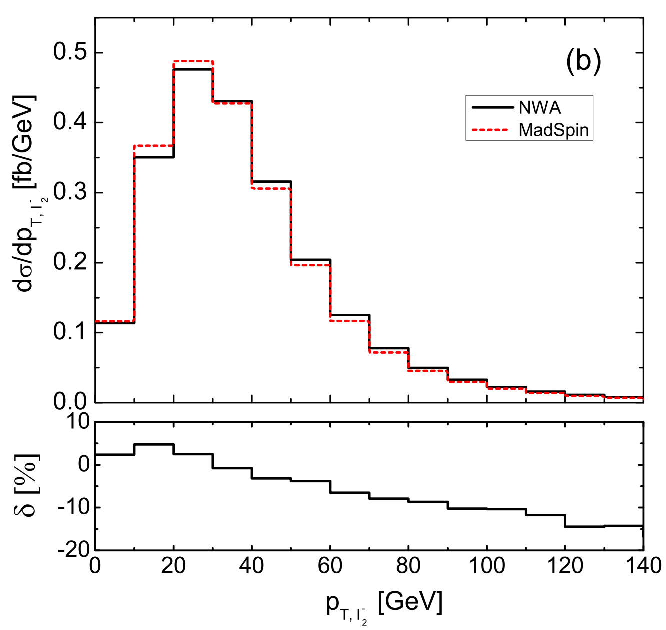
Cuts imposed on the first three hardest jets. It would be interesting to apply MiNLO on this process.

Fixed-order VV + jets recent results

- $W^+W^- + j$, NLO QCD $\mathcal{O}\left(\alpha^2\alpha_s^2\right)$ and EW $\mathcal{O}\left(\alpha^3\alpha_s\right)$ corrections (Li Wei-Hua, Zhang Ren-You, Ma Wen-Gan, Guo Lei, Li Xiao-Zhou, Zhang Yu, arXiv:1507.07332)
- $ZZ + j$, NLO QCD $\mathcal{O}\left(\alpha^2\alpha_s^2\right)$ and EW $\mathcal{O}\left(\alpha^3\alpha_s\right)$ corrections (Yong Wang, Ren-You Zhang, Wen-Gan Ma, Xiao-Zhou Li, Lei Guo, arXiv:1604.04080)



Sudakov logs

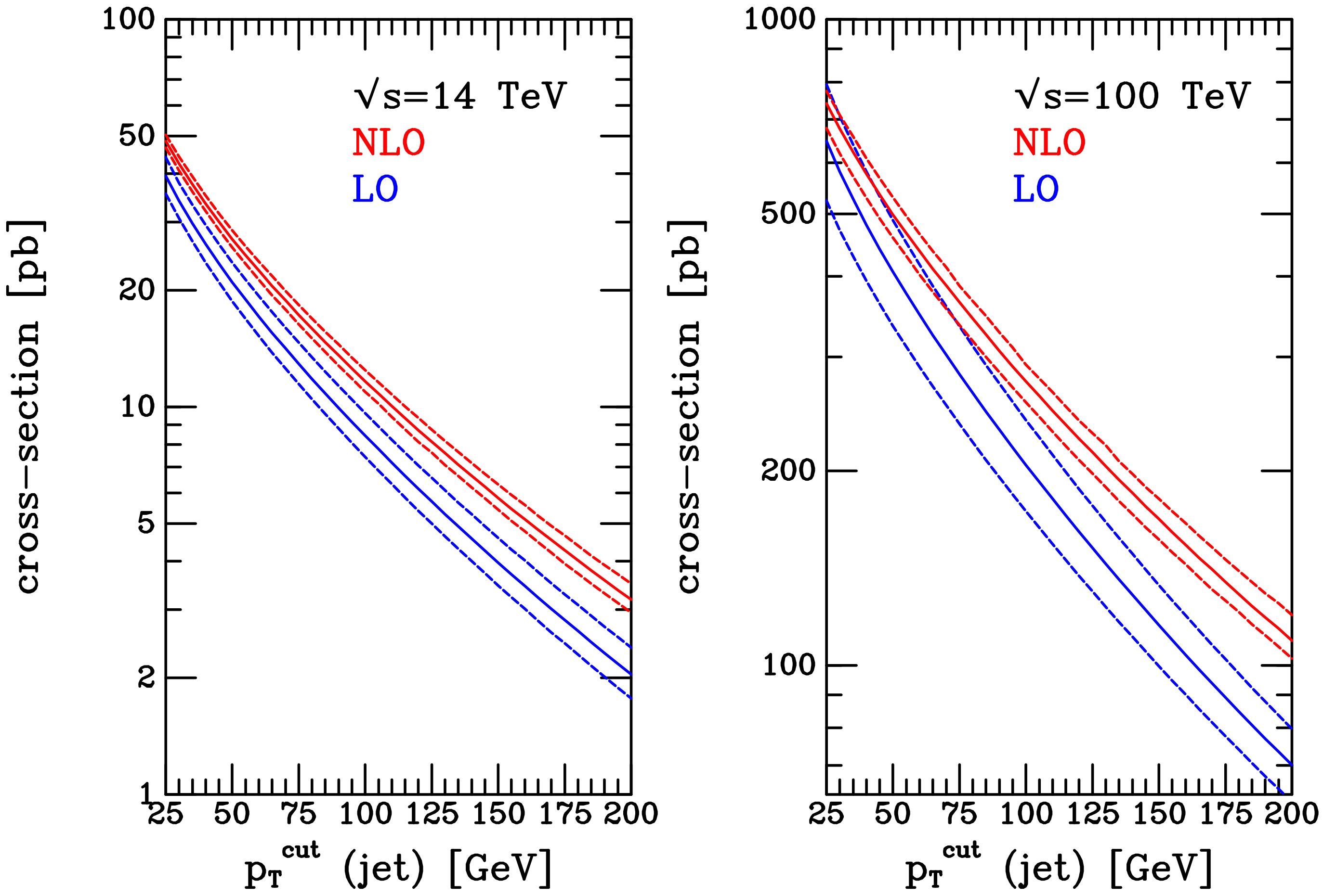


Spin-correlation effects

Leptonic decay treated in NWA or with `MadSpin` (so spin-correlation and finite-width effects are predicted with good accuracy). No EW corrections between final-state leptons and production.

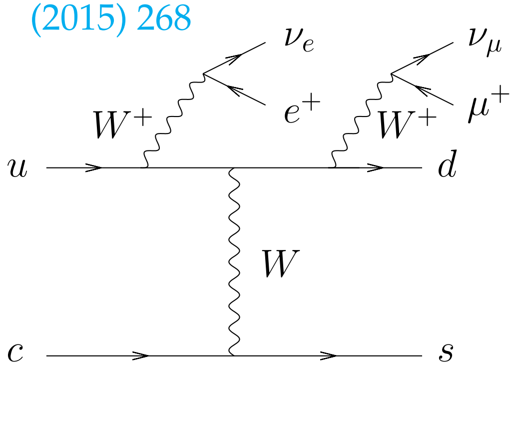
MCFM

- ✓ Several vector-boson production processes, both VBF/VBS and “QCD” type.
- ✓ NLO QCD corrections to $WW + 1$ jet, leptonic decay only, (Campbell, Miller, Robens, arXiv:1506.04801)
- ✓ `http://mcfm.fnal.gov/`



VBFNLO

- ✓ Several VVj, $VVjj$ and VVV processes at fixed order, NLO QCD and, in some cases, also EW.
- ✓ Possibility to study anomalous couplings to discriminate between SM and beyond-SM scenarios, by the introduction of higher dimensional operators.
- ✓ For a recent review, see Campanario, Kerner, Ninh, Rauch, Roth, Zeppenfeld, Nucl. Part. Phys. Proc. 261-262 (2015) 268



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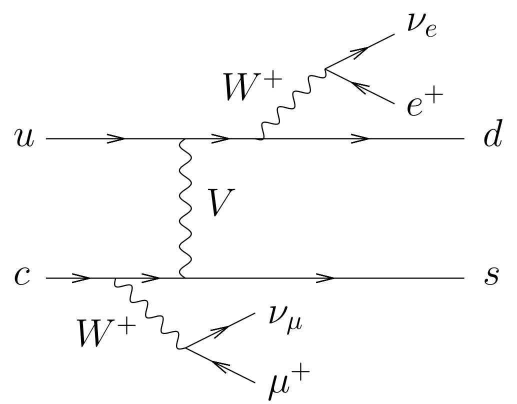
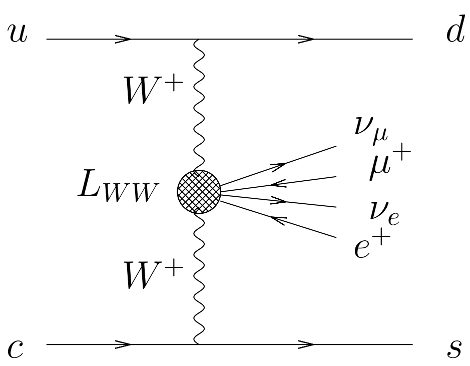
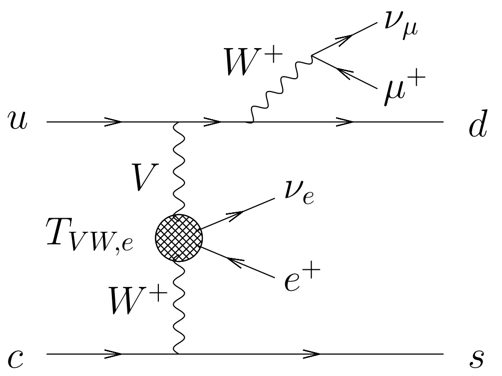


(b)

Notice that if the final state is $2j + 4\ell$, there are processes with no s-channel vector bosons. These are fully considered in VBFNLO



(c)



(d)

https://www.itp.kit.edu/vbfnlo

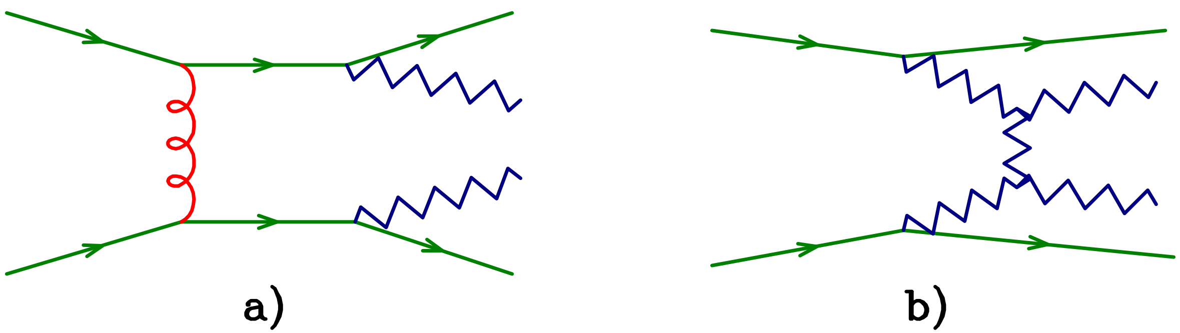
see Roth's talk tomorrow

Vector and multi-vector boson production in the POWHEG BOX

- QCD NLO + Parton Shower
  - W/Z plus leptonic decay $\mathcal{O}(\alpha^2)$: `W` and `Z`, (Alioli,Nason, C.O., Re, arXiv:0805.4202)
  - Wj/Zj plus leptonic decay $\mathcal{O}(\alpha^2\alpha_s)$: `Wj` and `Zj`, (Alioli,Nason, C.O., Re, arXiv:1009.5594)
  - Zjj plus leptonic decay $\mathcal{O}(\alpha^2\alpha_s^2)$: `Zjj`, (Re, arXiv:1204.5433)
  - Wjj and Zjj plus leptonic decay $\mathcal{O}(\alpha^2\alpha_s^2)$: `W2jet`, `Z2jet`, (Campbell, Ellis, Nason, Zanderighi, arXiv:1303.5447)
  - ZZ, WZ and W^+W^- production, including γ/Z interference, singly resonant contributions and interference for identical leptons $\mathcal{O}(\alpha^4)$, `ZZ`, `WZ`, `WW`
    $pp \to e^+e^-\mu^+\mu^+$ and $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$
    (Melia, Nason, Rontsch, Zanderighi; arXiv:1107.5051, Nason, Zanderighi, arXiv:1311.1365)

Vector and multi-vector boson production in the POWHEG BOX

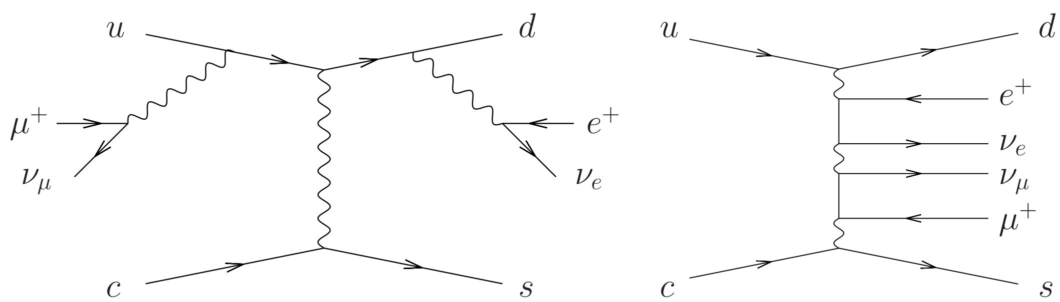
- QCD NLO + Parton Shower
  - $W^\pm W^\pm jj$ plus leptonic decay $\mathcal{O}\left(\alpha^4\alpha_s^2\right)$: `Wp_Wp_J_J`, (Melia, Nason, Rontsch, Zanderighi, arXiv:1102.4846)



$\mathcal{O}\left(\alpha^4\alpha_s^2\right)$ $\mathcal{O}\left(\alpha^6\right)$ VBF/VBS

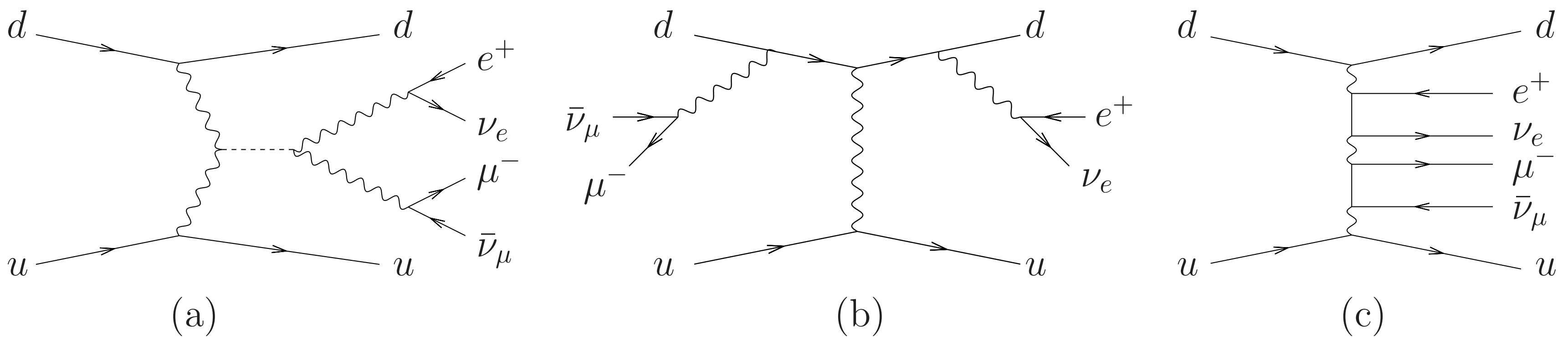
Vector and multi-vector boson production in the POWHEG BOX

- VBF/VBS, NLO QCD corrections
  - Zjj plus leptonic decay, $\mathcal{O}\left(\alpha^4\right)$: `VBF_Z` (Jäger, Schneider, Zanderighi, arXiv:1207.2626)
  - Zjj, Wjj plus leptonic decay, $\mathcal{O}\left(\alpha^4\right)$: `VBF_W-Z` (Schissler, Zeppenfeld, arXiv:1302.2884)
  - $W^{\pm}W^{\pm}jj$ plus leptonic decay, $\mathcal{O}\left(\alpha^6\right)$: `vbf_wp_wp` (Jäger, Zanderighi, arXiv:1108.0864)
    $pp \rightarrow e^+\nu_e\mu^+\nu_\mu jj$



- VBF/VBS, NLO QCD corrections

  – W^+W^-jj plus leptonic decay, $\mathcal{O}(\alpha^6)$: `VBF_Wp_Wm` (Jäger, Zanderighi, arXiv:1301.1695)
  $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu jj$



  – $ZZjj$ plus leptonic decay, $\mathcal{O}(\alpha^6)$: `VBF_Z_Z` (Jäger, Karlberg, Zanderighi, arXiv:1312.3252)
  $pp \to e^+ e^- \mu^+ \mu^- jj$

More processes in the following slides.

New and less-new features in the POWHEG BOX

- The presence of a divergent fixed-order Born cross section becomes inevitable when final states with high jet multiplicity are considered. This happens, for example, in Vj or $V\gamma$ production, with leptonic V decay, when the jet becomes collinear to the incoming beams or when the photon becomes collinear to the incoming beams or to the final-state charged leptons.
  This affects all processes like VV + jets
- Related to this (at least in the `POWHEG BOX`), the question of merging samples with different multiplicity, i.e. V, Vj, $Vjj\ldots$ samples, preserving the good features of each sample in the "appropriate" region of validity.
  We deal with divergent Born cross sections and with the merging of samples using MiNLO.
- While the generation of QCD radiation has been there from the beginning, the generation of QED radiation is a relatively new feature in the `POWHEG BOX`.
- Radiation from resonance decay. For example, massive vector and scalar bosons are not stable. They decay to other particles. When attaching NLO radiation to the decay products (both QCD or QED radiation) care must be taken in order to preserve the virtuality of the resonance near its peak and to keep track of the possible resonance histories of a given process.

MiNLO + NLO

- ✓ MiNLO: Multi-scale improved NLO (Hamilton, Nason, Zanderighi, arXiv:1206.3572)
- ✓ The purpose of MiNLO is to improve the NLO computation of inclusive quantities when regions of the phase space with widely different scales are approached.
- ✓ The MiNLO procedure has been inspired by the Catani-Krauss-Kuhn-Webber (CKKW) method. It achieves its goals by:
  - recursively clustering all the colored partons in the event using the k_T-clustering algorithm, in order to reconstruct the most likely branching history
  - at each of the vertexes of the branching history, it assigns a nodal scale q_i, equal to the relative transverse momentum at which the clustering has taken place

$$q_1 \le q_2 \le q_3 \le \ldots \le Q$$

    and use q_i as renormalization scale to compute the value of α_s at that vertex.
  - If the event is a real contribution, the first merging scale is called q_0

MiNLO + NLO

- Assign an appropriate Sudakov form factor to all external and to all intermediate lines

$$\Delta_f(Q, q_T) = \exp\left\{-\int_{q_T^2}^{Q^2} \frac{dq^2}{q^2} \alpha_s(q) \left[A_1 \log\frac{Q^2}{q^2} + B_1\right]\right\} \qquad f = q, g$$

  It exponentiates large logarithms present in the fixed NLO cross section

- Its expansion is given by

$$\Delta_f(Q, q_T) = 1 + \alpha_s \left[-\frac{1}{2} A_1 \log^2 \frac{q_T^2}{Q^2} + B_1 \log\frac{q_T^2}{Q^2}\right] + \mathcal{O}(\alpha_s^2)$$

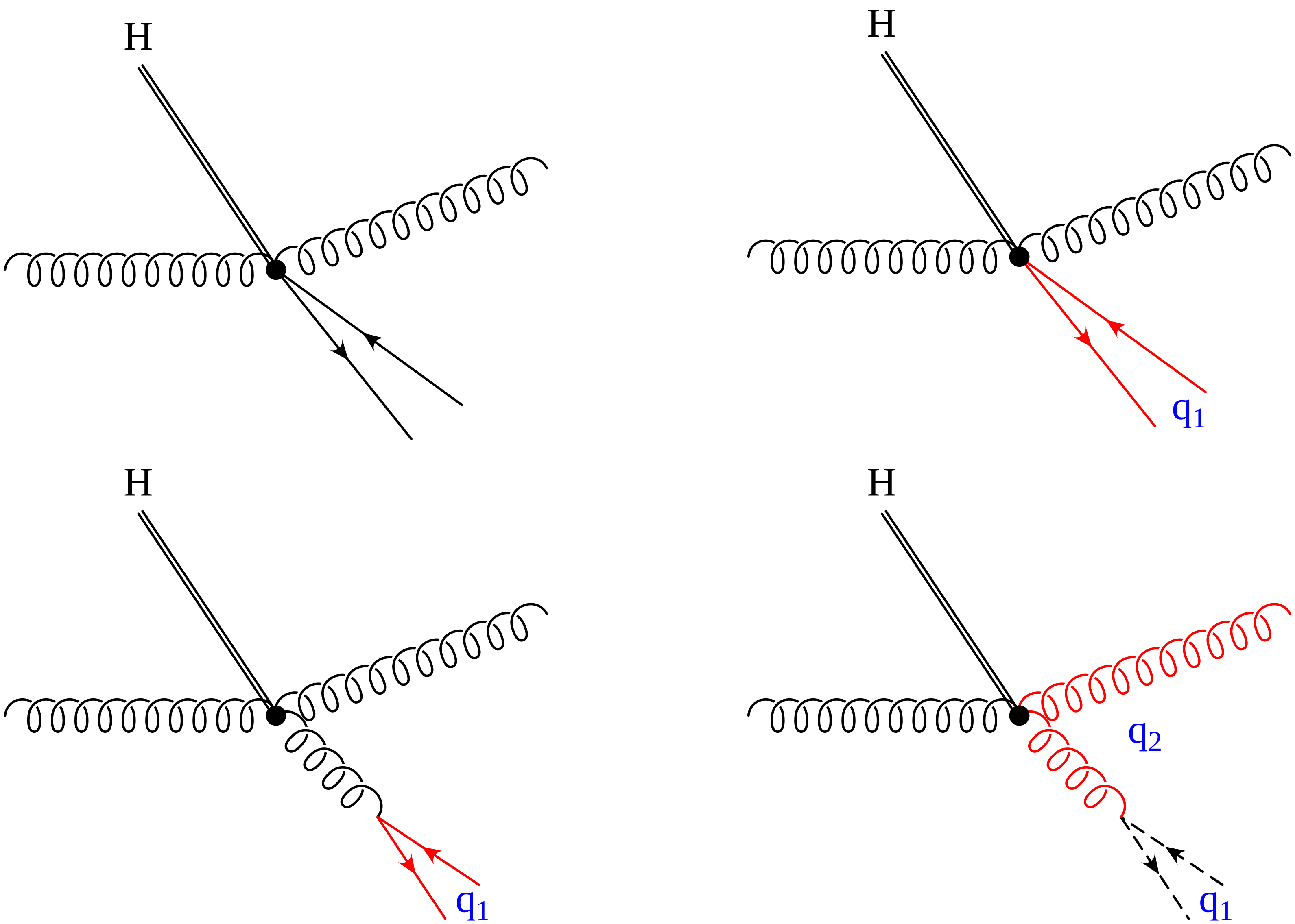
- At NLO, a Sudakov form factor contributes with a term proportional to the Born

$$B\,\alpha_s \left[-\frac{1}{2} A_1 \log^2 \frac{q'^2}{q^2} + B_1 \log\frac{q'^2}{q^2}\right]$$

  that need to be subtracted from the exact NLO differential cross section, since the NLO differential cross already contains such logarithmic contributions

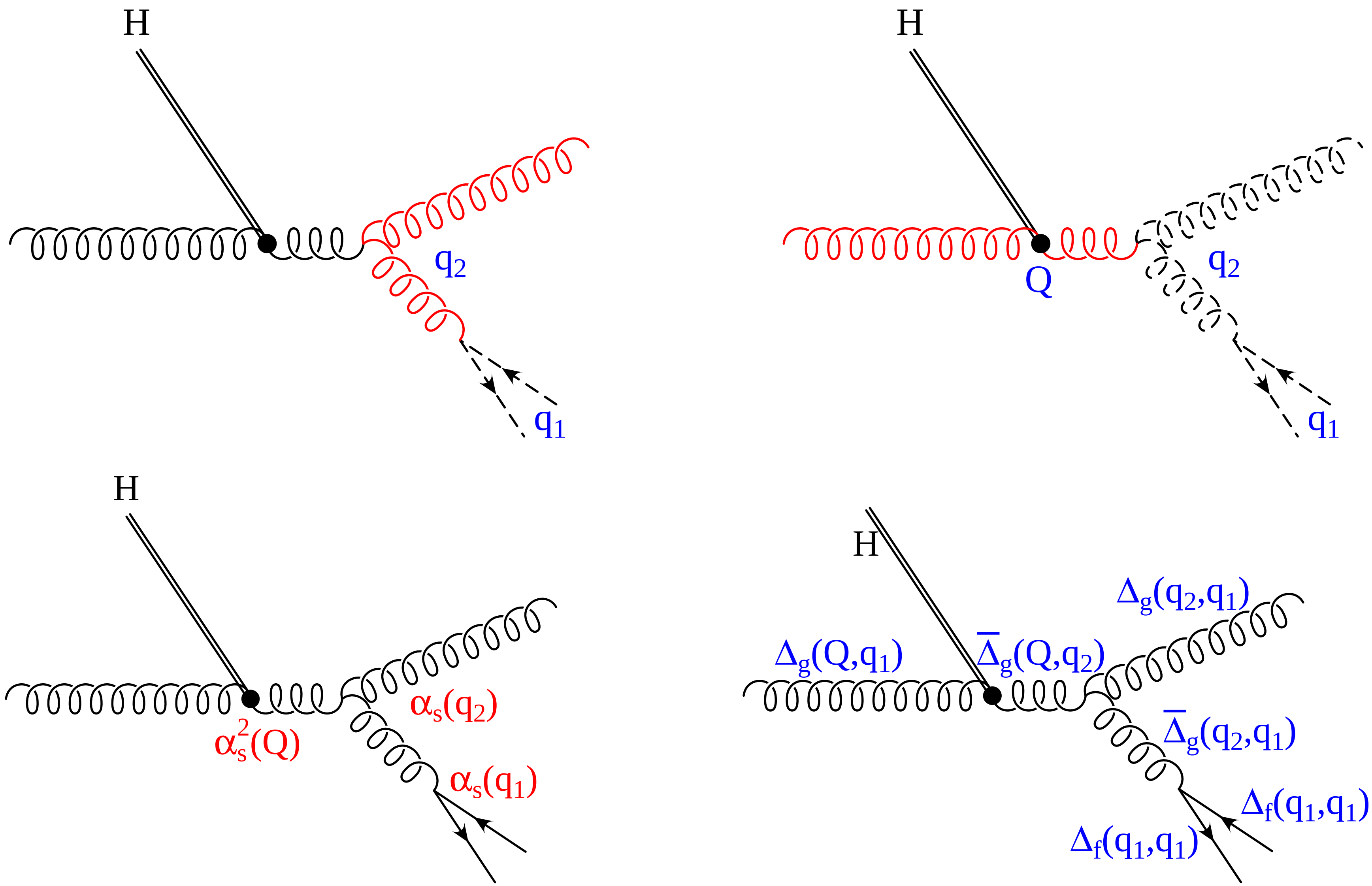
- set the factorization scale to q_1
- some degree of freedom is left for the value of the $(N+1)^{\text{th}}$ power of α_s in the real, in the virtual and in the expansion of the Sudakov form factor

MiNLO + NLO



Not Feynman diagrams, but the most likely branching history: $q_1 \leq q_2$

MiNLO + NLO



$q_1 \leq q_2 \leq Q$

$$\bar{\Delta}(q_i,q_j) \equiv \frac{\Delta(q_i,q_1)}{\Delta(q_j,q_1)}$$

MiNLO + NLO

✓ The full result has formal NLO accuracy, therefore the scale variation around the central values is formally of NNLO order

✓ The accuracy and the smooth behavior near the Sudakov regions is comparable to that of the corresponding tree-level calculation in the adopted CKKW scheme

✓ The procedure is simple and it can be easily implemented in any NLO-parton level generator, requiring only minor work on top of the NLO calculation available.

MiNLO + POWHEG

✓ The (simplified) POWHEG cross section is given by

$$d\sigma = \overline{B}(\mathbf{\Phi_B}) \left\{ \Delta\left(p_T^{min}\right) + \Delta(p_\mathrm{T}) \frac{R(\mathbf{\Phi_B}, \Phi_\mathrm{rad})}{B(\mathbf{\Phi_B})} \, d\Phi_\mathrm{rad} \right\} d\mathbf{\Phi_B}$$

$$\overline{B}(\mathbf{\Phi_B}) = B(\mathbf{\Phi_B}) + V(\mathbf{\Phi_B}) + \int d\Phi_\mathrm{rad} \, R(\mathbf{\Phi_B}, \Phi_\mathrm{rad})$$

$$\Delta(p_\mathrm{T}) = \exp\left[-\int d\Phi'_\mathrm{rad} \frac{R(\mathbf{\Phi_B}, \Phi'_\mathrm{rad})}{B(\mathbf{\Phi_B})} \, \theta\left(p'_\mathrm{T} - p_\mathrm{T}\right) \right]$$

✓ The underlying Born kinematics is generated with a probability proportional to the NLO inclusive cross section (the $\overline{B}$ term), at a given point in the Born phase space $\mathbf{\Phi_B}$

✓ The radiation jet is already accompanied by its Sudakov form factor

✓ We can then improve the POWHEG formula by implementing MiNLO on the inclusive $\overline{B}$ function

MiNLO + POWHEG

- ✓ The MiNLO approach improves the POWHEG implementations involving associated jet production, in the singular phase-space region.

- ✓ It provides a better match with the corresponding lower-multiplicity process.
  For example, $V + 2$ jets matches $V + 1$ jet when approaching the one-jet region, and $V + 1$ jet matches V when approaching the zero-jet region. See Hamilton, Nason, Zanderighi, arXiv:1206.3572 for more details.

- ✓ It turned out that it eases considerably the construction of matched samples with different jet multiplicities.

Merging samples

✓ Several codes provide NLO + Parton Shower results for the production of color-neutral object B (V, H, $VV\ldots$) plus 0, 1 and 2 jets

✓ Events produced with these Monte Carlo programs overlap in their population of the phase space, but the relative accuracies of each one in the various regions is complementary:

- the `B` generator
  * NLO accurate for inclusive boson distribution
  * LO accurate in the description of the hard radiation
- the `BJ` generator
  * NLO accurate for boson plus one jet distributions
  * LO accurate in the description of two jets
- ...

✓ Merging the `B`, `BJ`,...simulations means having a sample of events that

- has NLO accuracy for inclusive boson distributions
- has NLO accuracy for boson plus one jet distributions
- ...

MiNLO′ + POWHEG

We investigated the accuracy of the BJ+MiNLO results (Hamilton, Nason, C.O., Zanderighi, arXiv:1212.4504) and we found that:

✓ The inclusive boson observables are described by the BJ+MiNLO programs at relative order α_s with respect to the Born cross section. However, they do not reach NLO accuracy, since they also include ambiguous contributions of relative order $\alpha_s^{1.5}$, rather than α_s^2.

✓ It is possible to modify the BJ+MiNLO procedure in a very simple way in such a way that to reach NLO accuracy for inclusive observables $\Longrightarrow$ MiNLO′

✓ We can then produce a sample of "merged" events without actually merging different samples, i.e. no merging scale is needed.

✓ NNLO + Parton Shower accuracy on the inclusive B distribution can be reached

- H (Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017)
- W (Karlberg, Re, Zanderighi, arXiv:1407.2940)
- HW (Astill, Bizon, Re, Zanderighi, arXiv:1603.01620)

MiNLO′+POWHEG

The modifications are very simple:

✓ In the Sudakov form factor we have to include the A_2 and B_2 terms

$$\Delta(Q, q_{\mathrm{T}}) = \exp\left\{-\int_{q_{\mathrm{T}}^2}^{Q^2} \frac{dq^2}{q^2}\left[\left(A_1\alpha_s(q) + A_2\,\alpha_s^2(q)\right)\log\frac{Q^2}{q^2} + \left(B_1\alpha_s(q) + B_2\,\alpha_s^2(q)\right)\right]\right\}$$

✓ q_{T} is the transverse momentum of the produced boson.

✓ The value of the $(N+1)^{\mathrm{th}}$ power of α_s in the real, in the virtual and in the expansion of the Sudakov form factor has to be computed using q_{T} as renormalization scale.

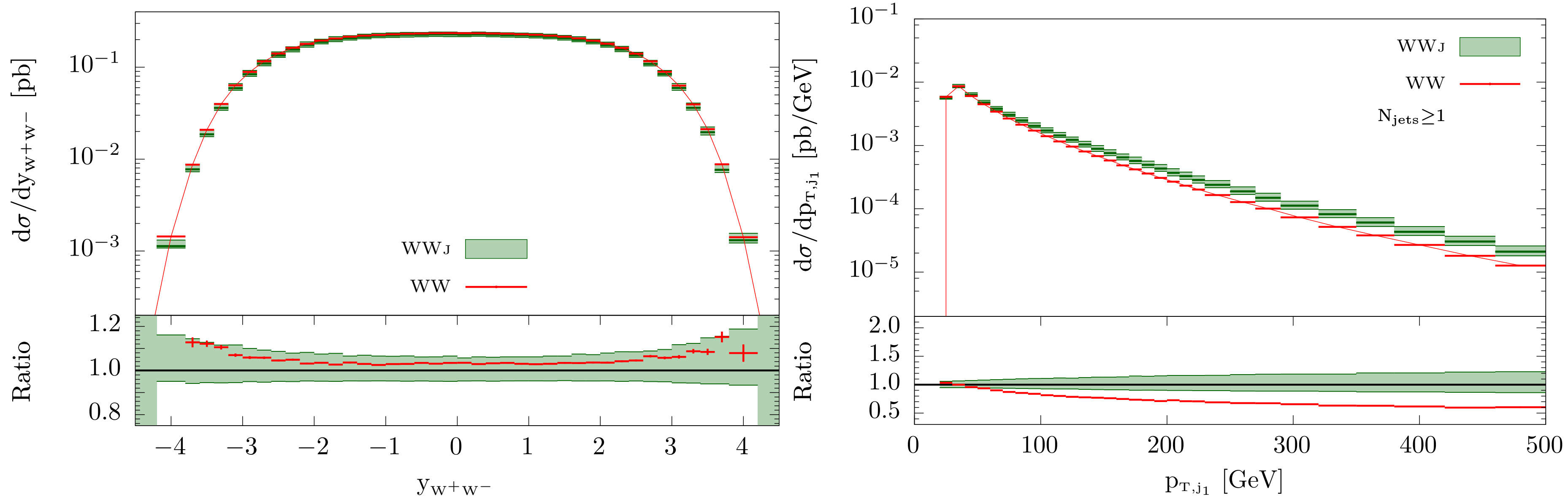
✓ The factorization scale has to be set to q_{T}.

Merging WW and WW + 1 jet with MiNLO'

Following the previous procedure, the first NLO + Parton Shower generator for W^+W^- and W^+W^- + 1 jet have been built (Hamilton, Melia, Monni, Re, Zanderighi, arXiv:1606.07062).

The resulting simulation achieves NLO accuracy not only for inclusive distributions in W^+W^- + 1 jet production but also for W^+W^- production, i.e. when the associated jet is not resolved, without the introduction of any unphysical merging scale.

Merging WW and WW + 1 jet with MiNLO′



- The rapidity of the W^+W^- pair has NLO accuracy with the `WW generator`. But it needs a cut on the first jet if computed with the `WWj` generator, if it is run without MiNLO. If MiNLO′ is active, the `WWj` generator predicts $y_{W^+W^-}$ with NLO accuracy
- The transverse momentum of the leading jet has LO accuracy with `WW generator`, but NLO accuracy with the `WWj` one.

The NLO EW corrections

As the precision of the experimental measurements at the LHC increases, NLO QCD corrections no longer suffice: NNLO QCD corrections are needed too.

- But NLO EW corrections are typically of the same order of NNLO QCD ones
- In addition, there are region of the phase space (large center-of-mass energy wrt vector-boson masses) where NLO EW effects contribute to 10-20% (Sudakov logarithms)

So, NLO EW corrections are needed too.

Photon radiation can be treated in a similar way as gluon radiation.

The first QCD+EW NLO corrections to simple processes have been available for some time.

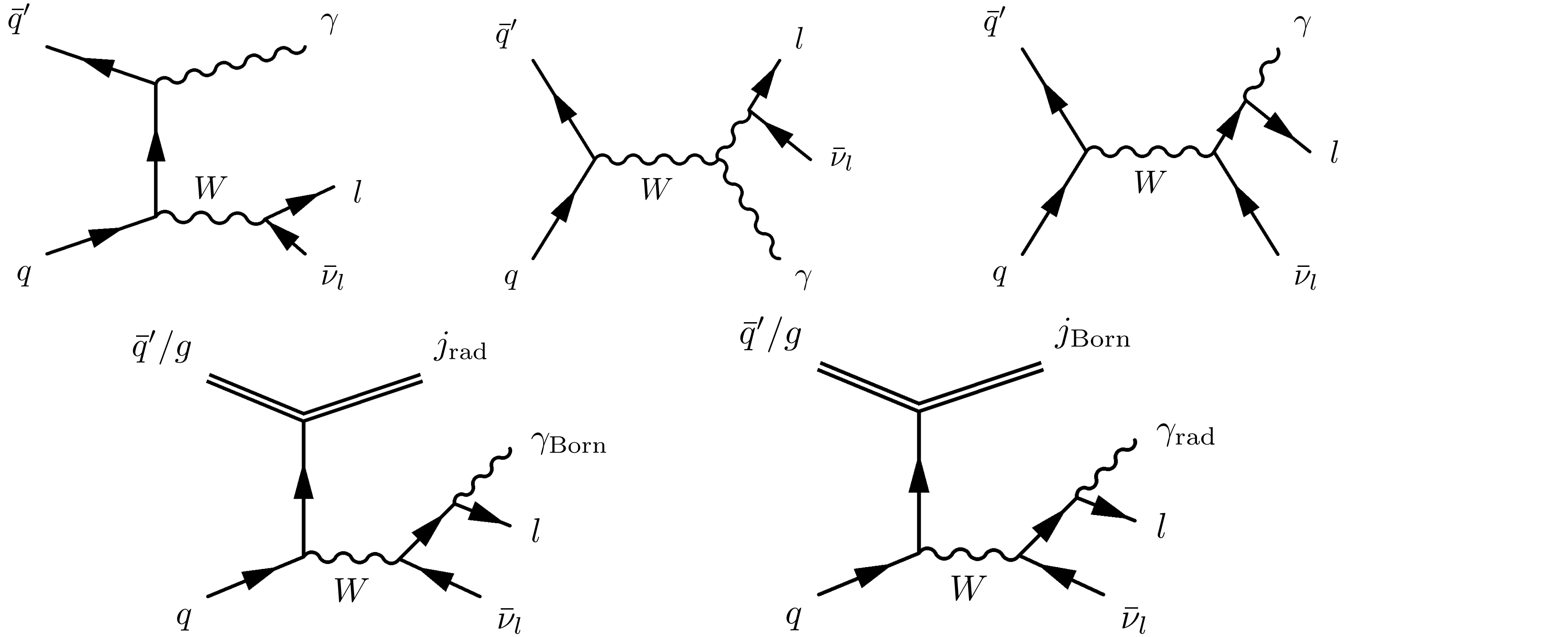
EW+QCD NLO + Parton Shower

- W plus leptonic decay: `W_ew-BMNNP` (Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465)
- Z plus leptonic decay: `Z_ew-BMNNPV` (Barzè, Montagna, Nason, Nicrosini, Piccinini, Vicini, arXiv:1302.4606)

Details on how QCD and QED radiation is generated and competes are given in the aforementioned papers.

QCD corrections with processes with photons

- $W\gamma$ (VV after all!): `Wgamma` (Barzè, Chiesa, Montagna, Nason, Nicrosini, Piccinini, Prosperi, arXiv:1408.5766)



This case is more complicated than QCD+EW radiation in W/Z production.
In fact, given the real contribution $W\gamma j$, this can be seen as generated by two different "underlying" Born processes:

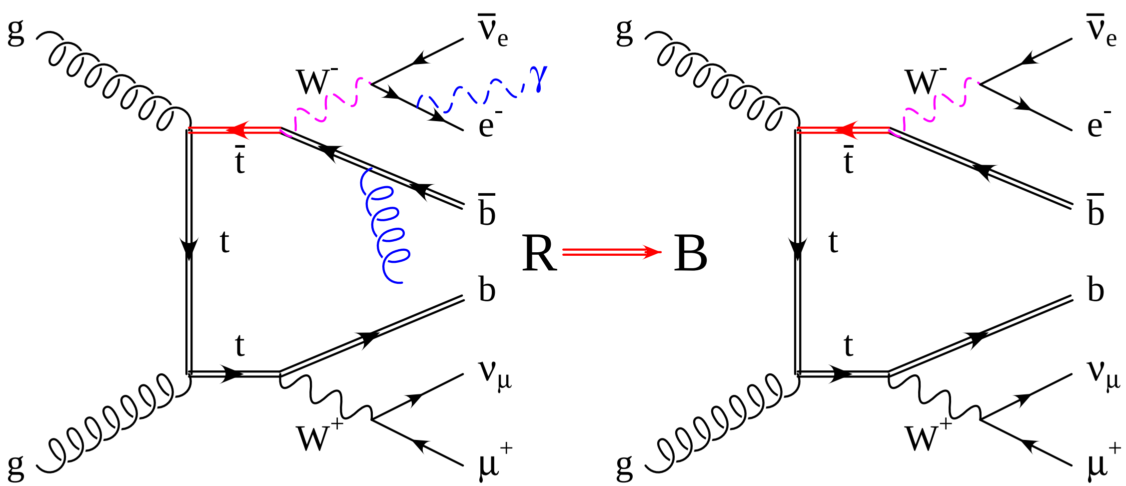
1. $pp \to W\gamma$, to which the `POWHEG BOX` attaches a radiated parton (for example a gluon) with the appropriate QCD Sudakov form factor.
2. or $pp \to Wj$, to which the `POWHEG BOX` attaches a photon with the appropriate QED Sudakov form factor.

QCD corrections with processes with photons

- $Z\gamma$ plus leptonic decay. To appear soon.

Resonaces

When dealing with resonances whose decay products can radiate, we have two more technical problems to tackle. Consider for example $e^-\bar{\nu}_e\mu^+\nu_\mu b\bar{b}$ ($VVbb$, this is part of VV production plus jets or $t\bar{t}$ production)



1) Problem at NLO level

Standard subtraction schemes to construct the counterterms to real diagrams (e.g. Catani-Seymour, Frixione-Kunszt-Signer/FKS) do not preserve the virtuality of the resonances. For example, when the $W^-\bar{b}g$ system is such that the $\bar{t}$ is on-shell, its counterterm is off-shell, spoiling infra-red cancellation in the narrow width approximation.

$$\mathbf{\Phi_R} \Longrightarrow (\mathbf{\Phi_B}, \Phi_{\rm rad}), \qquad\qquad \mathbf{\Phi_B} = \text{underlying Born}$$

Resonaces

2) Problem at NLO + Parton Shower level

The POWHEG formula is

$$d\sigma = \overline{B}(\mathbf{\Phi_B}) \left\{ \Delta\left(p_T^{min}\right) + \Delta(p_\mathrm{T}) \frac{R(\mathbf{\Phi_B}, \Phi_\mathrm{rad})}{B(\mathbf{\Phi_B})} \, d\Phi_\mathrm{rad} \right\} d\mathbf{\Phi_B}$$

$$\overline{B}(\mathbf{\Phi_B}) = B(\mathbf{\Phi_B}) + V(\mathbf{\Phi_B}) + \int d\Phi_\mathrm{rad} \, R(\mathbf{\Phi_B}, \Phi_\mathrm{rad})$$

$$\Delta(p_\mathrm{T}) = \exp\left[- \int d\Phi'_\mathrm{rad} \frac{R(\mathbf{\Phi_B}, \Phi'_\mathrm{rad})}{B(\mathbf{\Phi_B})} \, \theta(p'_\mathrm{T} - p_\mathrm{T}) \right]$$

The standard FKS POWHEG underlying Born mapping does not preserve resonance virtuality: if R is on shell, B is off shell, and R/B is LARGE. But, in POWHEG, R/B should be small (of the order of α_s), or should approach the Altarelli-Parisi splitting functions, for the method to work.

The POWHEG BOX RES

The solutions have been discussed in Jezo, Nason, arXiv:1509.09071. The output of this has been a major revision of the POWHEG BOX V2 code: the POWHEG BOX RES.

- For each flavour structure, the code automatically finds all the possible resonance histories compatible with the partonic process at hand and keeps track of them, while generating radiation from each resonance.
- A new mapping scheme that preserve the virtuality of resonances has been computed.

Tested on single-top and $\ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b\bar{b}$ production, a non-trivial production process, due to its complexity (Ježo, Lindert, Nason, C.O., Pozzorini, arXiv:1607.04538)

Interfaces to MadGraph, Gosam, OpenLoops

What if your favorite process is not in the POWHEG BOX?
There are automatic interfaces to matrix-element generators that can help generating the code used by the POWHEG BOX:

1. MadGraph 4: this has been used several times to generate Born, spin- and color-correlated amplitudes, real contributions and color flow for Born and (regular) real subprocesses (Campbell, Ellis, Frederix, Nason, C.O., Williams, arXiv:1202.5475)
2. Gosam 2.0: this has been used a few times to generate the virtual contributions (Luisoni, Nason, C.O., Tramontano, arXiv:1306.2542)
3. OpenLoops 1.3.1: this is brand new. Used for the first time for $\ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b\bar{b}$ production (Težo, Lindert, Nason, C.O., Pozzorini, arXiv:1607.04538)

All the limitations in the generation of processes is now only due to the capabilities of the previous codes to generate the Born, real and virtual corrections.

With some hacking, it is possible to extract the code for the matrix elements for Born, real and virtual diagrams from MadGraph5_aMC@NLO too. Hope to have an interface soon.

Conclusions and outlooks

✓ The POWHEG BOX V2 already contains several VV (+ jets) production processes.

✓ In the new release, the POWHEG BOX RES, the consistent treatment of resonances has been added.

- Given a list of possible partonic processes contributing to a particular production process, the program automatically finds all the possible resonance histories, and generates radiation by maintaining the virtuality of the decaying resonances.
- In addition, the automated phase-space integrator adapts itself to the given resonance history, in order to perform the correct importance sampling.

✓ The generation of QED radiation has been fully implemented in the POWHEG BOX RES, and NLO QCD+EW corrections can be generated at the same time.

✓ The POWHEG BOX RES benefits from the interface to three automatic matrix-element generators: MadGraph 4, Gosam and OpenLoops.

✓ It is then ready to be used for the generation and study of processes with higher jet multiplicities and decaying particles.

`http://powhegbox.mib.infn.it/`