POWHEG for ElectroWeak physics .

Simone Alioli
LBNL & UC Berkeley

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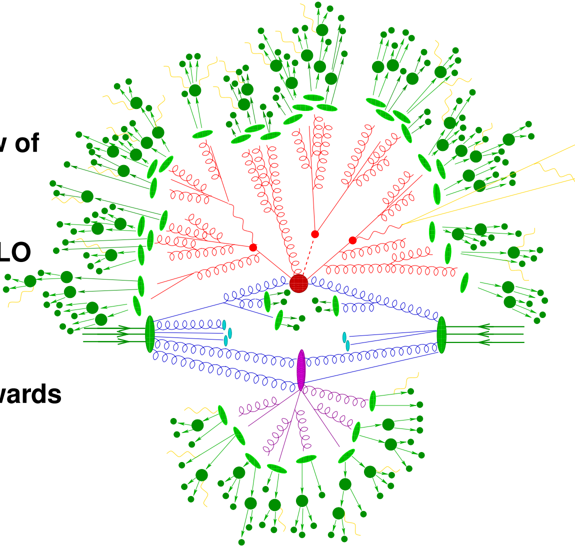
Duke Workshop: Electroweak Measurements at the Energy Frontier

Outline

- The POWHEG method
- The POWHEG BOX: overview of available EW processes
- Scale setting and the MINLO approach
- Merging different NLO multiplicities and road towards NNLO+PS generation
- Conclusions & Outlook



The POWHEG method

[Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

1. **Generates only the hardest emission including full tree level real matrix element and virtual corrections.**
2. **The shower generates subsequent emissions, performing (N)LL resummation of collinear/soft logs.**
3. **Vetoing emissions harder than the first is required to avoid double-counting.**

NLO differential cross section:

- **Phase space factorization :** $d\Phi_{n+1} = d\Phi_n \, d\Phi_{\rm rad} \qquad d\Phi_{\rm rad} \div dt\, dz\, \frac{d\varphi}{2\pi}$
- **NLO cross section at fixed underlying Born kinematics:** $d\sigma_{\tt NLO} = \bar{B}(\Phi_n) d\Phi_n d\Phi_{\rm rad}$

$$d\sigma_{\tt NLO} = \left\{ B(\Phi_n) + V(\Phi_n) + \Big[\underbrace{\overbrace{R(\Phi_n,\Phi_{\rm rad})}^{\rm IR divergent} - \overbrace{C(\Phi_n,\Phi_{\rm rad})}^{\rm IR divergent}}_{\rm finite} \Big] d\Phi_{\rm rad} \right\} d\Phi_n$$

$$V(\Phi_n) = \underbrace{\overbrace{V_b(\Phi_n)}^{\rm IR divergent} + \overbrace{\int C(\Phi_n,\Phi_{\rm rad})\, d\Phi_{\rm rad}}^{\rm IR divergent}}_{\rm finite}$$

The POWHEG method [Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

SMC differential cross section for first emission:

$$d\sigma_{\mathtt{SMC}} = \overbrace{B(\Phi_n)}^{Born}\, d\Phi_n \left\{ \Delta_{\mathtt{SMC}}(t_0) + \Delta_{\mathtt{SMC}}(t) \overbrace{\frac{\alpha_S(t)}{2\pi}\frac{1}{t}P(z)}^{\lim_{k_T\to 0} R(\mathbf{\Phi}_{n+1})/B(\mathbf{\Phi}_n)} d\Phi_{\mathrm{rad}}^{\mathtt{SMC}} \right\}$$

$$\Delta_{\mathtt{SMC}}(t) = \underbrace{\exp\left[-\int d\Phi'_{\mathrm{rad}} \frac{\alpha_S(t')}{2\pi}\frac{1}{t'} P(z')\,\theta(t'-t)\right]}_{\mathtt{SMC}\ Sudakov}$$

- **The event weight is** $B(\Phi_n)$
- $\Delta_{\mathtt{SMC}}(t)$ **is the probability of not emitting at a scale greater than** t **(**q^2**,** θ^2**,** p_T^2**)**
- **Unitarity ensures that what is inside** $\left\{\ldots\right\}$ **does not change the cross section**

  (up to t_0 **power suppressed terms)**

The POWHEG method [Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

The POWHEG differential cross section :

$$d\sigma_{\texttt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\texttt{POWHEG}}(\Phi_n, p_T^{\min}) + \Delta_{\texttt{POWHEG}}(\Phi_n, k_T) \frac{R(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)}\, d\Phi_{\text{rad}} \right\}$$

- ✓ **NLO cross section for inclusive quantities. Event weight is $\bar{B}(\Phi_n)$**

- ✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}})]\, d\Phi_{\text{rad}} < 0$

  Negative weights where NLO $>$ LO, i.e. where perturbative expansion breaks down!

- ✓ **Probability of not emitting with transverse momentum harder than p_T:**

$$\Delta_{\texttt{POWHEG}}(\Phi_n, p_T) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(k_T(\Phi_n, \Phi'_{\text{rad}}) - p_T\right) \right]$$

- ✓ **It has the same logarithmic accuracy of the SMC. In the soft/collinear region $k_T \to 0$**

$$\frac{R(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)} d\Phi_{\text{rad}} \approx \frac{\alpha_S(t)}{2\pi} \frac{1}{t} P(z)\, dt\, dz\, \frac{d\varphi}{2\pi} \quad \textbf{and} \quad \bar{B} \approx B\,(1 + \mathcal{O}(\alpha_S))$$

- ✓ **The accuracy of NLO is preserved in the hard region, since $\Delta_{\texttt{POWHEG}}(\Phi_n, p_T) \approx 1$ and**

$$d\sigma_{\texttt{POWHEG}} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n, \Phi_{\text{rad}})\, d\Phi_n\, d\Phi_{\text{rad}} \approx R(\Phi_n, \Phi_{\text{rad}})\,(1 + \mathcal{O}(\alpha_S))\, d\Phi_n\, d\Phi_{\text{rad}}$$

A common view of POWHEG and MC@NLO

$$d\sigma = \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}} d\Phi_n \overbrace{\left\{ \Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t) \frac{R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)} \, d\Phi_{\text{rad}} \right\}}^{\text{sum to 1 by unitarity}}$$

$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) \right]}_{\text{NLO}} d\Phi_n \, d\Phi_{\text{rad}}$$

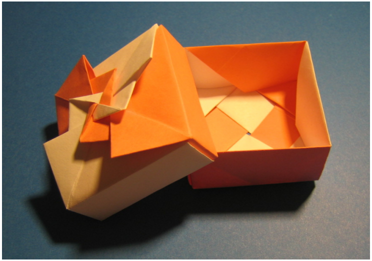
$$\bar{B}_{\text{sing}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}}) \right] d\Phi_{\text{rad}}$$

$$\Delta_{\text{sing.}}(t) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right) \right]$$

- **In POWHEG :** $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) = F(\Phi_n, \Phi_{\text{rad}}) \times R(\Phi_n, \Phi_{\text{rad}})$**, with** $0 \leq F \leq 1$**, and** $F(\Phi_n, \Phi_{\text{rad}}) \to 1$ **in the soft/collinear limit.** $F = 1$ **valid choice, often employed.**

- **In MC@NLO :** $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) = R_{\text{SMC}}(\Phi_n, \Phi^{\text{SMC}}_{\text{rad}})$ **is the shower approximation of a real emission.**

The POWHEG BOX [S.A., Nason,Oleari,Re, JHEP 1006:043,2010]



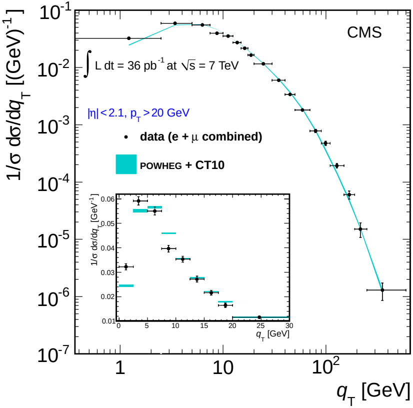
- Framework for the implementation of a POWHEG generator for a generic NLO process
- Practical implementation of the theoretical construction of the POWHEG general formulation presented in [Frixione,Nason,Oleari,JHEP 0711:070, 2007]
- FKS subtraction approach automatically implemented, hiding all the technicalities
- Code publicly available at the web page http://powhegbox.mib.infn.it
- Few other groups implement their own version (SHERPA ,HERWIG++) or use the POWHEG BOX interfaced to specific NLO calculator (POWHEL)

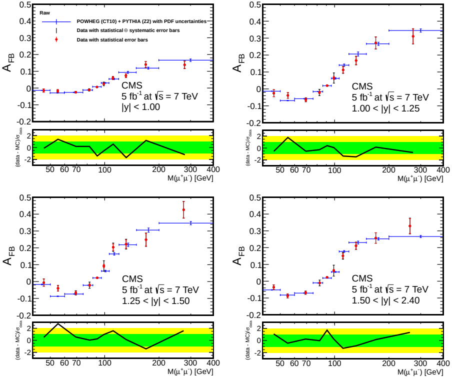
Automated NLO + PS predictions in the POWHEG BOX

- To implement new processes the user was required to provide a few inputs. Now (almost) everything has been fully automated.
- However, the freedom of using dedicated routines at any stage is left.
- Ingredients:
  - The list of flavour of Borns and Reals $\Longleftarrow$ **Madgraph**
  - The Born phase space $\Longleftarrow$ **Dedicated routines, recursive FKS, multi-channel**
  - The Born squared amplitudes $\mathcal{B} = |\mathcal{M}|^2$, the color-ordered Born squared amplitudes $\mathcal{B}_{jk}$ and the helicity correlated Born squared amplitudes $\mathcal{B}_{k,\mu\nu}$ $\Longleftarrow$ **Madgraph**
  - The Real squared amplitudes $\mathcal{R}$ $\Longleftarrow$ **Madgraph**
  - The finite part of the interference of Born and virtual amplitude contributions $\mathcal{V}_{\mathrm{b}} = 2\mathrm{Re}\{\mathcal{B} \times \mathcal{V}\}$ $\Longleftarrow$ **GoSam, BlackHat, MadLoop**

- Given these ingredients the `POWHEG BOX` automatically finds singular regions, performs the FKS subtraction and outputs the results of a NLO analysis.
- Then it produces events with a single extra radiation (or not), ready to be showered with your preferred SMC, via the Les Houches interface.
- Drivers for fortran SMC provided. Support of open standards allow for easy interface to modern `C++` SMC (`Pythia8, Herwig++`) and to the `Rivet` analysis toolkit

- Includes interference Z/γ^{*}, full leptonic decays and correlations





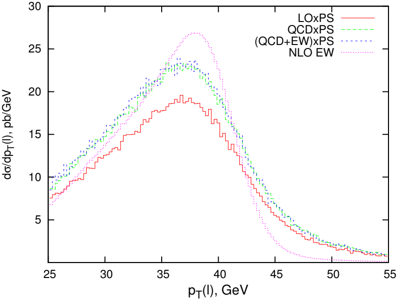
- Extensively tested and widely used by experimental collaborations.

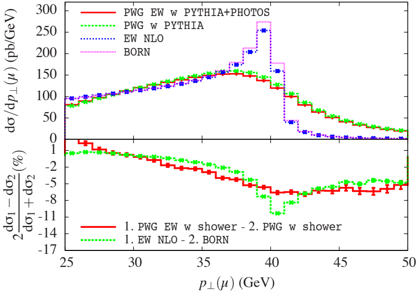
$W^{\pm}$ production with NLO QCD and NLO EW

[Bernaciak, Wackeroth, arXiv:1201.4804]

[Barzè et al., arXiv:1202.0465]

- **Two different implementation:**
  - **NLO QCD + NLO EW, only 1st QCD emission by POWHEG. Interfaced to QCD parton shower (`PYTHIA` / `HERWIG`). No photon-induced nor multiple photon radiation.**
  - **Simultaneous NLO QCD and QED correction on first emission by POWHEG, interfaced to QCD (`PYTHIA`) and QED (`PHOTOS`) parton showers. Modification of the POWHEG BOX structure to handle quasi-collinear QED radiation.**

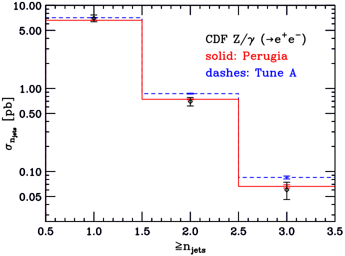


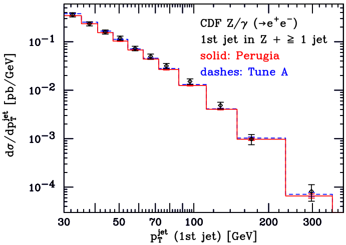


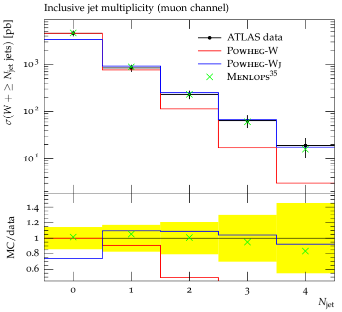
- **Much more on this in Alessando's talk....**

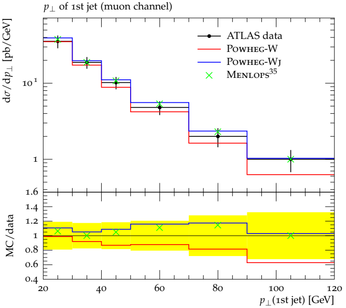
$W^{\pm}$ or Z plus one jet

[SA, Nason, Oleari & Re JHEP 1101, 2011]





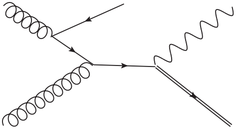
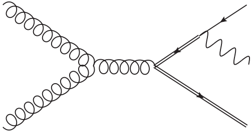




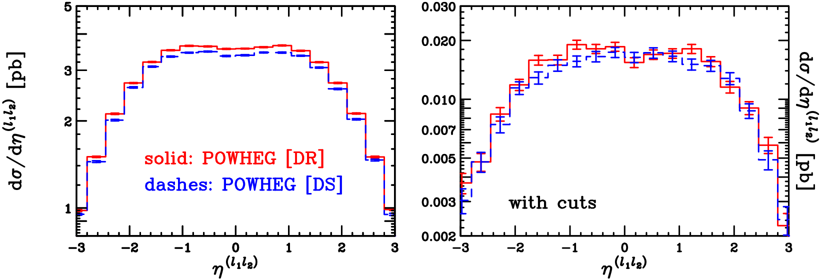
- **Currently a lot of theoretical interest in merging samples with different multiplicities, see later.**

Associated production of a W and a top-quark [E. Re, Eur. Phys. J. C71, 2011]

- Process ill-defined beyond LO, due to interference with $t\bar{t}$ plus decay

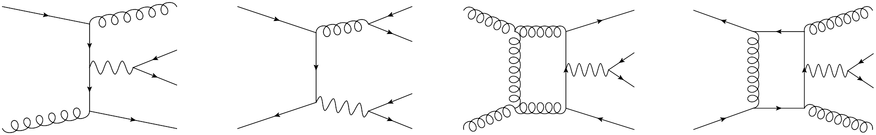
- Need to perform a gauge invariant subtraction to cancel the doubly resonant $t\bar{t}$ constribution. Same as in `MC@NLO`.

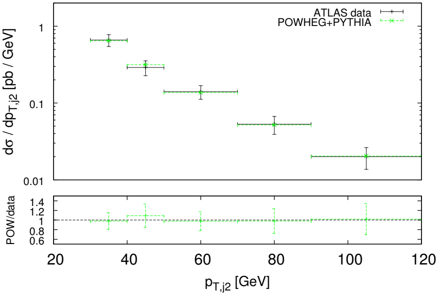


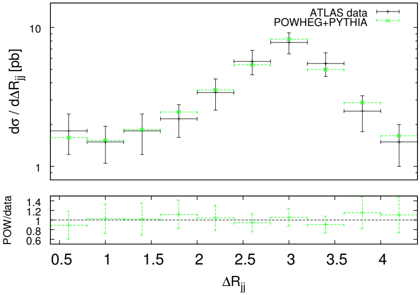
Z plus two jets, QCD induced

[E. Re, JHEP 1210, 2012]

- **QCD induced, Z/γ^* interference, full leptonic decays**



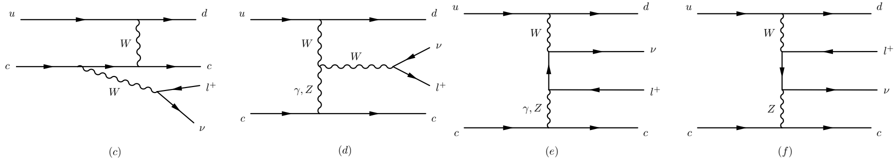


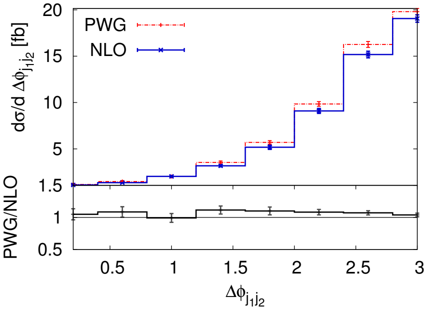


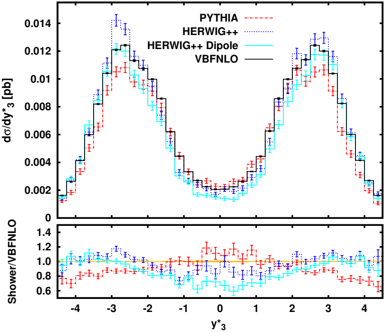
$Z, W^{\pm}$ plus two jets, EW induced

[B. Jager,S. Schneider, G. Zanderighi, arXiv:1207.2626]
[F. Schissler, D.Zeppenfeld, arXiv:1302.2884]

- **Interfaced to VBFNLO, interference to diboson negligible within VBF cuts**



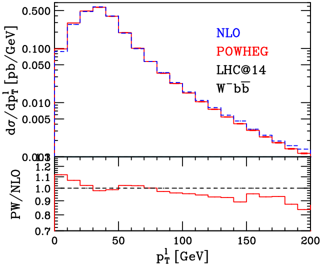


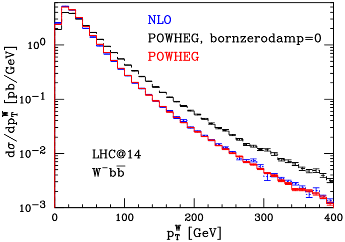


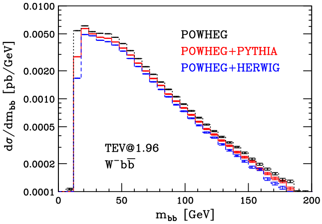
$W b\bar{b}$

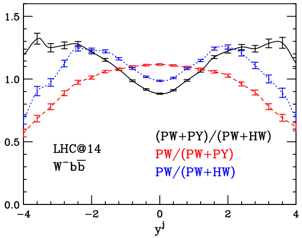
[Oleari,Reina arXiv 1105.4488]

- **Massive $b-$quarks and approx. leptonic decay correlations**





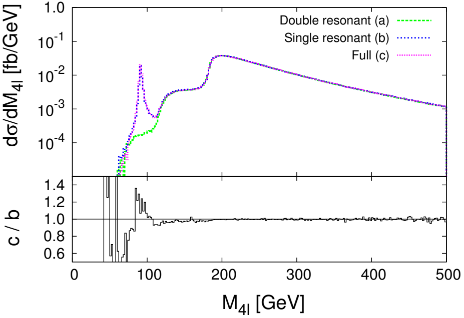


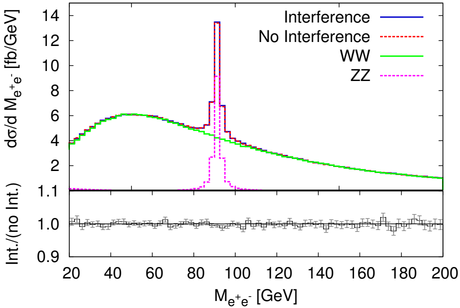


Di-boson production: $ZZ, W^+W^-, ZW^\pm$

[Melia et al. JHEP 1111 (2011) 078]

- **Includes Z/γ^* interference, singly resonant graphs and identical fermions interference.**
- **Negligible interference between $W^+W^- \to \ell^+\ell^-\nu\bar{\nu}$ and $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ not included**
- **Also no isolated photons in the final state.**





Anomalous triple gauge couplings in di-boson production

- **Include possibility to study ATGC : most general terms for the WWV vertex ($V = \gamma, Z$) parametrized by a C and P conserving**

$$\mathcal{L}_{\text{eff}} = ig_{WWV} \left(g_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + \kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_2 W^*_{\mu\nu} W^\nu_\rho V^{\rho\mu}} \right)$$

- **In the SM $g_1^V = \kappa_1^V = 1$, and $\lambda^V = 0$**
- **All 6 parameters can be set independently in `POWHEG`.**
- **Imposing EM gauge invariance Δg_1^γ vanishes.**
- **Limiting to dimension six operators only 3 are left (LEP) , e.g.**

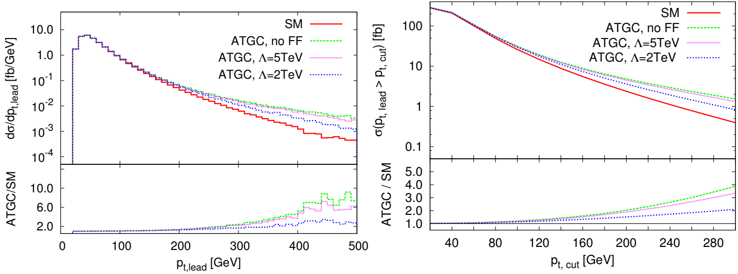
$$\Delta g = -0.027, \qquad \Delta\lambda = \Delta\lambda^\gamma = -0.044, \qquad \Delta\kappa^\gamma = -0.112$$

- **Can include form factor to avoid unitarity violation at high energy**

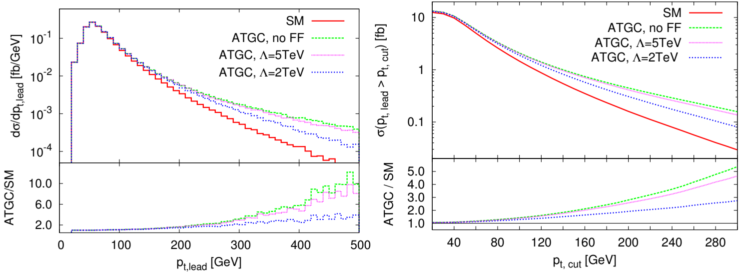
$$\Delta g \to \frac{\Delta g}{(1+M^2/\Lambda^2)^2}$$

Anomalous triple gauge couplings in di-boson production

- W^+W^-

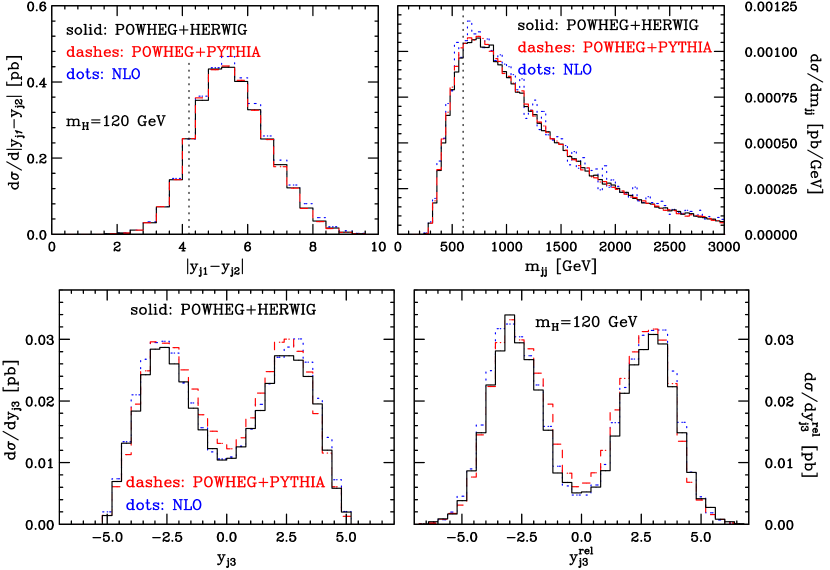


- W^-Z



Higgs boson production via VBF

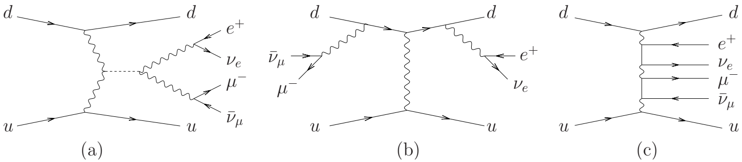
[P. Nason & C. Oleari, JHEP 1002, 2010]

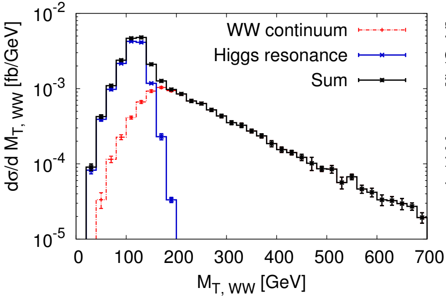


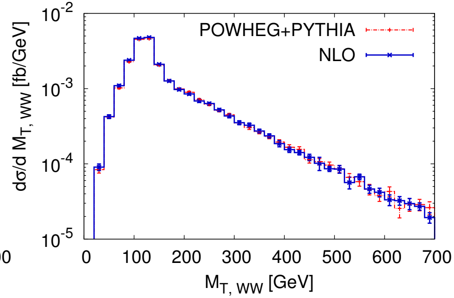
Electroweak W^+W^-jj production

[B. Jager & G. Zanderighi arXiv 1301.1695]

- **Includes full leptonic decays, resonant and non-resonant contributions**

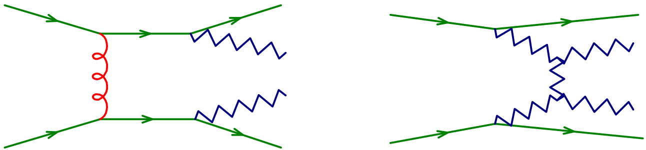




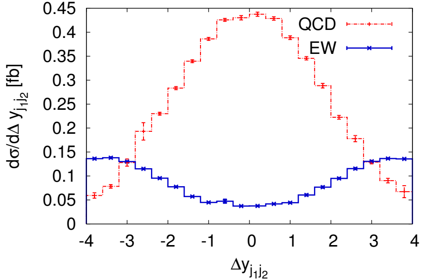


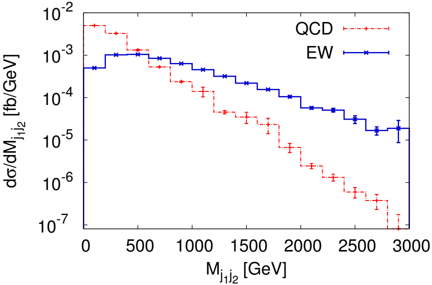
W^+W^+jj production, QCD and VBF

[Melia et al. Eur.Phys.J. C71 (2011) 1670]
[Jaeger,Zanderighi JHEP 1111 (2011) 055]



- **Contributions disentagled via rapidity and invariant mass cuts**

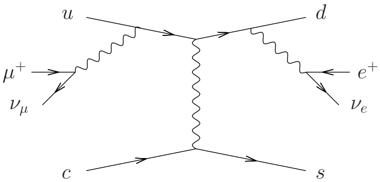


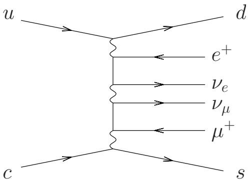


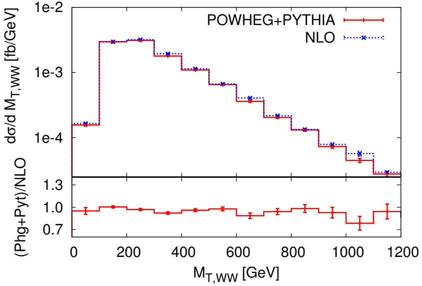
W^+W^+jj production, QCD and VBF

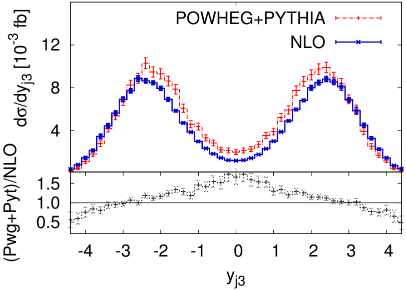
[Melia et al. Eur.Phys.J. C71 (2011) 1670]
[Jaeger,Zanderighi JHEP 1111 (2011) 055]

- Leptonic decays and non-resonant contributions included.





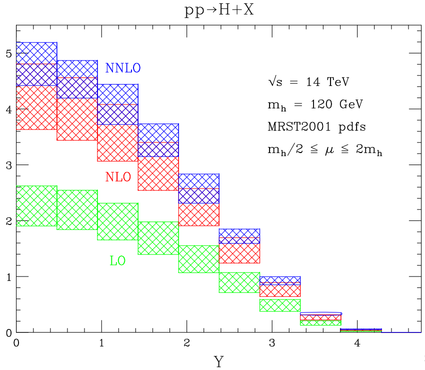


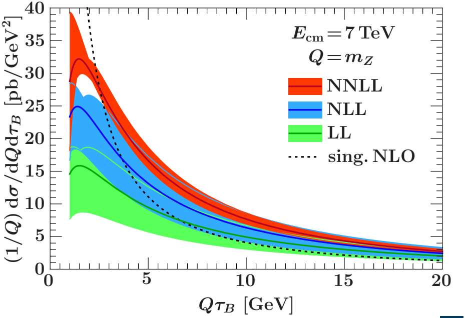


- With leptonic decays is a $2 \to 6$ process: computationally very intensive.
- No problems to implement it in the `POWHEG BOX`, only few modifications of the internal `POWHEG BOX` routines to handle it efficiently.

Scale setting and MINLO: preliminary considerations

- **Common lore is to identify "correct" scales *a posteriori*, e.g. by requiring small corrections or to minimize sensitivity**
- **Motivated by the fact that poor scale choice will result in large logs, giving large NLO corrections and large sensitivity.**
- **However, large corrections can have physical origins: new channels, large color factors, large logs of IR origin, etc ...**
- **Better be careful to avoid mixing together unrelated physics, by forcing/adjusting the scales to produce small corrrections or sensitivity.**

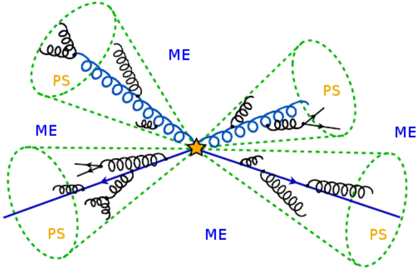




Multiscale Improved NLO

[K. Hamilton, P.Nason & G.Zanderighi arXiv:1206.3572]

- Based on CKKW idea: cluster the event to create a splitting history, at each splitting provide a coupling constant, evaluated at the scale of the splitting. For each leg between splittings, include a Sudakov factor.



- Two basic requirements to maintain NLO accuracy :
  - Enforce scale compensation by fixing the scales in virtuals and reals up to NNLO or by adding a compensating term.
  - Subtract the extra logs generated by Sudakov $\otimes$ Born, already accounted for in the NLO calculations.

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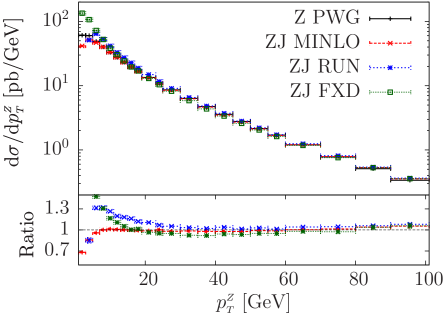
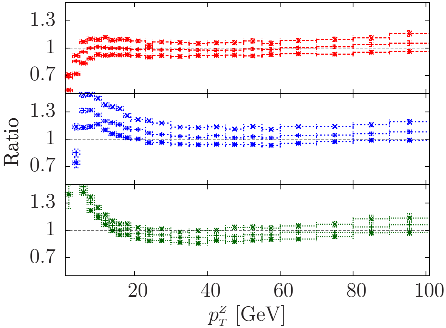




- Theoretically sound scale choice for processes with extra jets, defined *a priori*, which takes care of large Sudakov logs
- NLO accuracy of V+ 1 jet not spoiled, the predictions are always finite also with extra jets close to soft/coll. limit at Born level.
- NLO accuracy of V only if doing V production and MINLO scale choice, not so for V + 1 or V + 2 jets.
- Method applied to H+ up to 2 jets and V+ up to 2 jets
- Very easily implemented and ready to use in the `POWHEG BOX` : obtain more stable NLO+PS simulations

MINLO 2.0 : merging without merging scale

[K. Hamilton et al. arXiv:1212.4504]

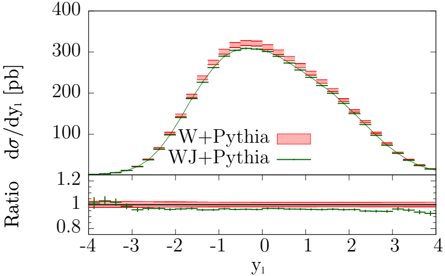
Extending the MINLO idea:

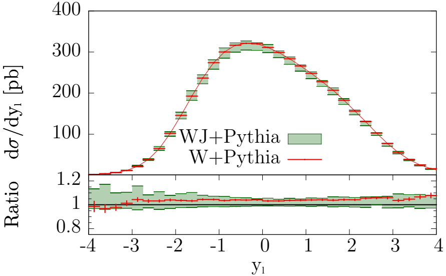
- **MINLO 1.0 was not NLO for V alone, due to spurious $\mathcal{O}(\sqrt{\alpha_S})$ terms**
- **MINLO 2.0 applied to V+1 jet can obtain V predictions which are NLO accurate.**
- **Merging avoided by inclusion of higher order terms in Sudakov exponent B_2 (NNLL) and careful scale choice $\alpha_s(q_T^V)$**

$$\Delta_g\left(Q, q_T\right) = \exp\left\{ -\int_{q_T^2}^{Q^2} \frac{dq^2}{q^2} \left[A\left(\alpha_S\left(q^2\right)\right) \log\frac{Q^2}{q^2} + B\left(\alpha_S\left(q^2\right)\right) \right] \right\}$$

$$A\left(\alpha_S\right) = \sum_{i=1}^{\infty} A_i\, \alpha_S^i, \qquad B\left(\alpha_S\right) = \sum_{i=1}^{\infty} B_i\, \alpha_S^i$$

- **No need to introduce a merging scale**
- **Example W^- at TeVatron**





First steps towards NNLO+PS

- **Consider Higgs production at fixed m_H, only 1 LO variable y_H**
- **HJ MINLO achieves $\mathcal{O}(\alpha^3)$ for V inclusive observable and $\mathcal{O}(\alpha^4)$ for VJ ones**
- **Reweighting the VJ MINLO `POWHEG` output with**

$$\frac{\left(\frac{d\sigma}{dy_H}\right)_{\texttt{H NNLO}}}{\left(\frac{d\sigma}{dy_H}\right)_{\texttt{HJ MINLO}}} = \frac{c_2\alpha_S^2 + c_3\alpha_S^3 + c_4\alpha_S^4}{c_2\alpha_S^2 + c_3\alpha_S^3 + d_4\alpha_S^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_S^2 + \mathcal{O}(\alpha_S^3).$$

  it is in principle possible to build a NNLO + PS generator:

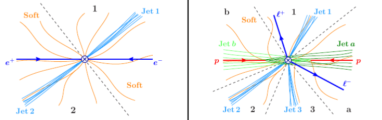
  - **Reweighting does not spoil $\mathcal{O}(\alpha^4)$ for VJ, but only generates $\mathcal{O}(\alpha^5)$ terms, beyond NNLO accuracy.**
  - **Inclusive distributions are reweighted to $\mathcal{O}(\alpha^4)$ across the whole phase space.**

- **With more complicated processes, reweighting should be done as a function of each LO variable**
- **MINLO 2.0 limited to only one extra emission at the moment. Requires inclusion of NNLL terms, not present in the shower. Not yet clear if possible to extend it to larger multiplicities, with available higher-order resummations.**

A different approach: GENEVA

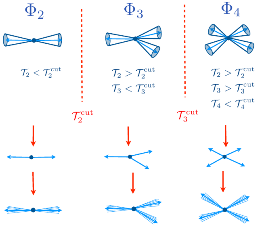
[SA, C. Bauer et al. arXiv:1211.7049]

- **The NLO merging problem can be solved by employing a phisical resolution variable, $N-$jettiness, with good resummation properties**



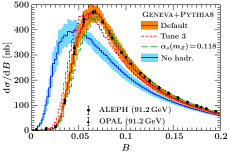
$$\mathcal{T}_N = \frac{2}{Q^2}\sum_k \min\{q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$

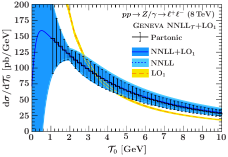
$$\mathcal{T}_N = \frac{2}{Q^2}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$



- **Opportunely partitioning the phase-space and assigning NLO jet-cross sections based on $N-$jettiness, it's possible to merge several different multiplicities.**
- **Parton showering is allowed only within resolution cuts (PS $\rightarrow$ Resummation)**
- **Interfaced to hadronization.**

- **Large logarithms in the resolution variable cuts resummed at higher-order.**





Conclusions and Outlook

- POWHEG is a well established method to implement NLO corrections into SMC programs.
- The POWHEG BOX includes a sizeable list of EW processes implementations, easily accessible as a tool to obtain NLO+SMC predictions (also many other QCD and Higgs processes not listed here see http://powhegbox.mib.infn.it)
- The choice of scales is still a sensible point when multiple scales are present, MINLO proposal has nice features and is easily implementable.
- Recently there has been a lot of works and ideas on how to combine NLO simulations with different multiplicity.
- The key point seems the need of higher-order resummation, in order to mantain the effective NLO accuracy after merging.
- The implementation of a NNLO+PS generator might not be far away ...

Thank you for your attention!