KrkNLO in Herwig 7

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with

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`arXiv:1607.06799`

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Outline

Herwig 7

A major new release of the Monte Carlo event generator Herwig++ (version 3.0) is now available. This release marks the end of distinguishing Herwig++ and HERWIG development and therefore constitutes the first major release of version 7 of the Herwig event generator family. The new version features a number of significant improvements to the event simulation, including: built-in **NLO** *hard process calculation for all Standard Model processes, with matching to both angular-ordered and* **dipole shower** *modules via both* **subtractive (MC@NLO-type)** *and* **multiplicative (Powheg-type)** *algorithms; QED radiation and spin correlations in the angular ordered shower; a consistent treatment of perturbative uncertainties within the hard process and parton showering.*

`herwig.hepforge.org`   `arXiv:1512.01178`

Motivation

- NLO QCD calculations are now the default in event generators
- MC@NLO and Powheg approaches are already well-established and are widely used.
- Why would we want another?
  - Extremely simple
  - No negative-weight events
  - Fast
  - Simplicity at NLO hopefully leads to simplifications for NNLO+NLOPS

KrkNLO

The main advantage of the KrkNLO method with respect to other methods of matching the fixed-order NLO calculations with PSMCs (MC@NLO and POWHEG) is its simplicity, which stems from the fact that the entire NLO corrections are implemented using a **simple, positive, multiplicative MC weight** *in combination with* **pre-calculated MC-scheme PDFs**.

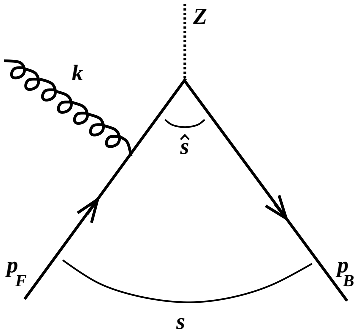
Drell-Yan

$$s = (p_1 + p_2)^2$$

$$\alpha = \frac{p_2 \cdot k}{p1 \cdot p2}, \qquad \beta = \frac{p_1 \cdot k}{p1 \cdot p2}$$

$$z = \frac{\hat{s}}{s} = 1 - \alpha - \beta$$

$$k_T^2 = \alpha\beta s$$



Basic Idea of the MC Scheme

DY cross-section at NLO in collinear $\overline{\mathrm{MS}}$ factorization for the $q\bar{q}$ channel:

$$\sigma^1_{\mathrm{DY}} - \sigma^B_{\mathrm{DY}} = \sigma^B_{\mathrm{DY}} D_1^{\overline{\mathrm{MS}}}(x_1, \mu^2) \otimes \frac{\alpha_s}{2\pi} C_q^{\overline{\mathrm{MS}}}(z) \otimes D_2^{\overline{\mathrm{MS}}}(x_2, \mu^2)$$

where

$$C_q^{\overline{\mathrm{MS}}}(z) = C_F \left\{ 4(1+z)^2 \left[\frac{\ln(1-z)}{1-z}\right]_+ - 2\frac{1+z^2}{1-z}\ln(z) + \delta(1-z)\left(\frac{2}{3}\pi^2 - 8\right)\right\}$$

Solutions for NLO+PS match which use $\overline{\mathrm{MS}}$ PDFs need to implement the **collinear remnant** term that that is a technical artefact of $\overline{\mathrm{MS}}$.

The implementation is not simple since those terms correspond to the collinear limit, but the Monte Carlo lives in 4-dimensions and not in the phase space resitrcted by $\delta(k_T^2)$.

The idea behind the MC scheme is to absorb those terms into the PDFs.

MC Scheme PDFs

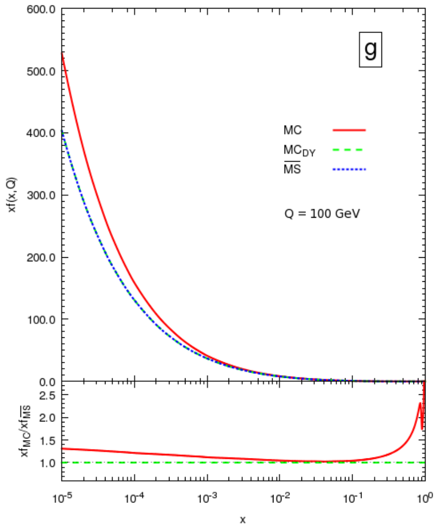
Transforming $\overline{\mathrm{MS}}$ PDFs to MC PDFs: [arXiv:1606.00355]

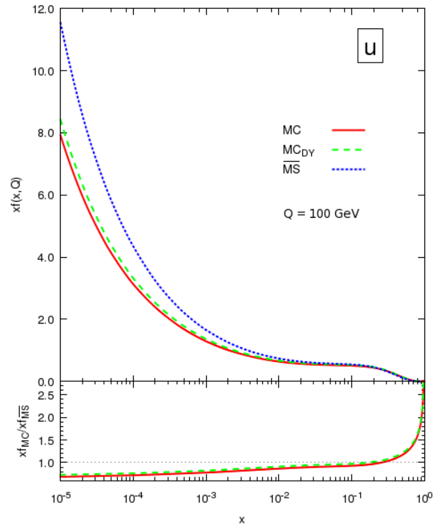
$$\begin{bmatrix} q_(x,Q^2) \\ \overline{q}(x,Q^2) \\ g(x,Q^2) \end{bmatrix}_{\mathrm{MC}} = \begin{bmatrix} q_(x,Q^2) \\ \overline{q}(x,Q^2) \\ g(x,Q^2) \end{bmatrix}_{\overline{\mathrm{MS}}} + \int \mathrm{d}y\, \mathrm{d}z\, \delta(x-yz) \begin{bmatrix} K_{qq}^{\mathrm{MC}}(z) & 0 & K_{qg}^{\mathrm{MC}}(z) \\ 0 & K_{\overline{q}\overline{q}}^{\mathrm{MC}}(z) & K_{\overline{q}g}^{\mathrm{MC}}(z) \\ K_{gq}^{\mathrm{MC}}(z) & K_{g\overline{q}}^{\mathrm{MC}}(z) & K_{gg}^{\mathrm{MC}}(z) \end{bmatrix} \begin{bmatrix} q_(x,Q^2) \\ \overline{q}(x,Q^2) \\ g(x,Q^2) \end{bmatrix}_{\overline{\mathrm{MS}}}$$

see backup slides for $K(z)$

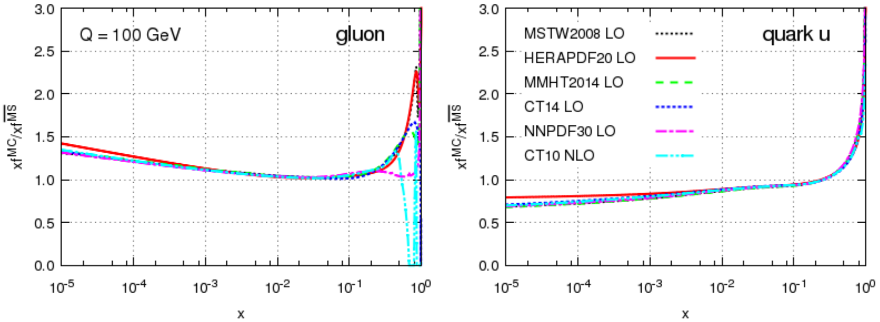
- Original MC (MCDY) PDFs were only used for Drell-Yan, gluon PDFs were identical.
- Processes with initial state gluons need full MC PDFs
- PDFs already generated for CT10, CT14, HERAPDF, MMHT, MSTW2008, NNPDF3.0
- Available in LHAPDF6 format
- We provided all information (MC-scheme coeff. functions, Q2 evolution governed by LO kernels) needed for direct fitting of PDFs!

MC Scheme PDFs





MC-Scheme



- Ratio of MC PDFs to their $\overline{\mathrm{MS}}$ counterparts

KrkNLO

1. Take a parton shower that covers the (α,β) phase space completely (no gaps, no overlaps) and produces emissions according to approximate real matrix element K.

2. Upgrade the real emissions to exact ME R by reweighting the parton shower events by $W_R = R/K$.

3. We define the coefficient function $C^R(z) = \int(R - K)$. To avoid unphysical artefacts of $\overline{\mathrm{MS}}$.

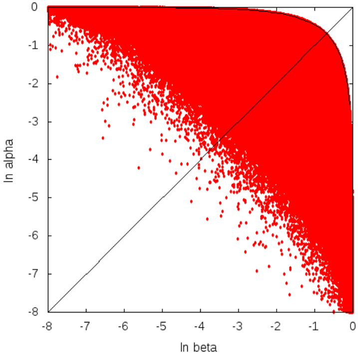
4. Transform PDF for $\overline{\mathrm{MS}}$ scheme to this new physical MC factorization scheme.

5. As a result the virtual+soft correction, Δ_{VS}, is just a constant, without z-dependent collinear remnant terms. Multiply the whole result by $1 + \Delta_{VS}$ to achieve complete NLO accuracy.

Implementation

Ingredients

- Herwig 7 LO matrix element
- Herwig 7 Dipole Shower (k_T-ordered)
- MC Scheme PDF
- Real weight, W_R
- Virtual+Soft weight, W_{VS}
- Choice of α_s argument for R and VS



Drell-Yan

We get **simple** weights!

- Real
  - $q\ \bar{q}\ \rightarrow\ Z\ g$

$$W_R^{q\bar{q}}(\alpha,\beta) = 1 - \frac{2\alpha\beta}{1+z^2}$$

  - $q\ g\ \rightarrow\ Z\ q$

$$W_R^{qg}(\alpha,\beta) = 1 + \frac{\beta(\beta+2z)}{z^2+(1-z)^2}$$

$$W_R^{qg}(\alpha,\beta) = W_R^{gq}(\beta,\alpha)$$

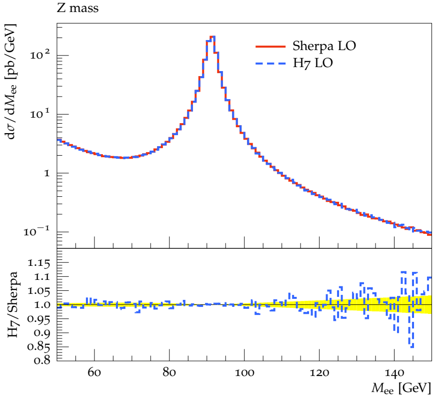
- Virtual+Soft, $W_{VS} = 1 + \Delta_{VS}$

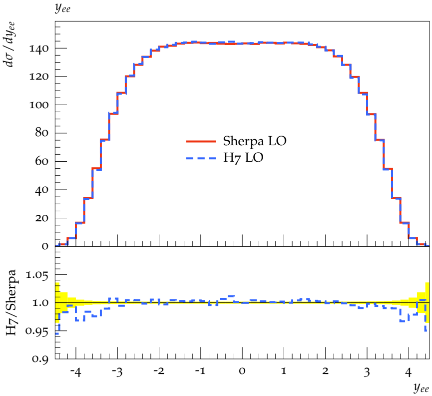
$$\Delta_{VS}^{q\bar{q}} = \frac{\alpha_s}{2\pi}\, C_F \left(\frac{4}{3}\pi^2 + \frac{1}{2}\right), \qquad \Delta_{VS}^{qg} = 0$$

Drell-Yan

Leading Order

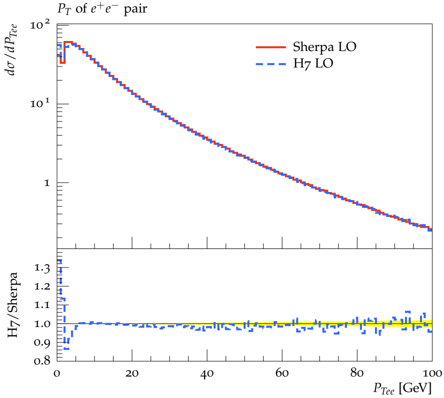
- Validate new implementation by comparing to previous Sherpa implementation

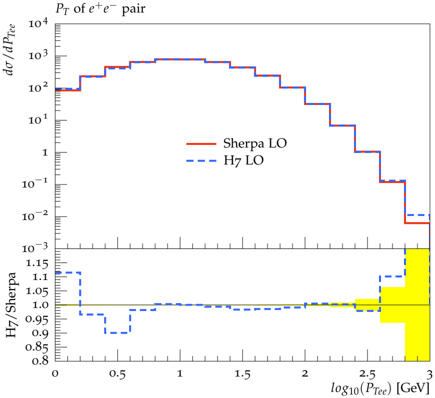




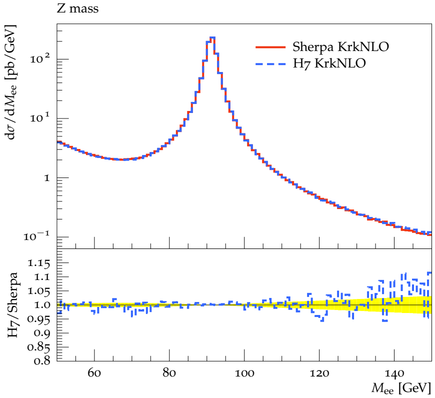
Drell-Yan

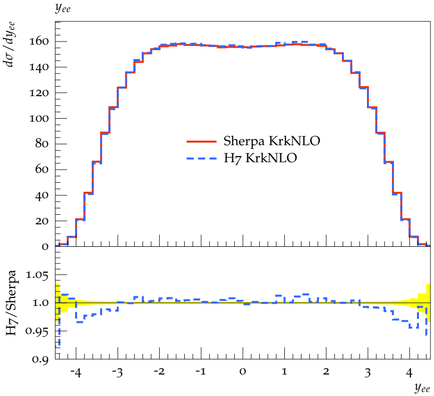
Leading Order



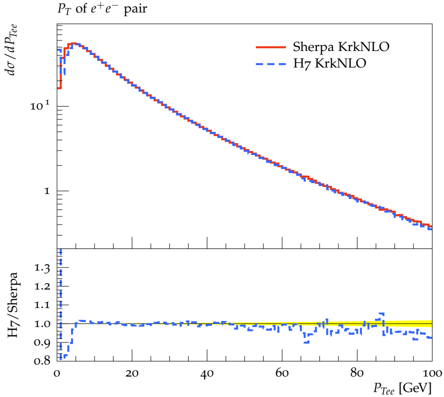


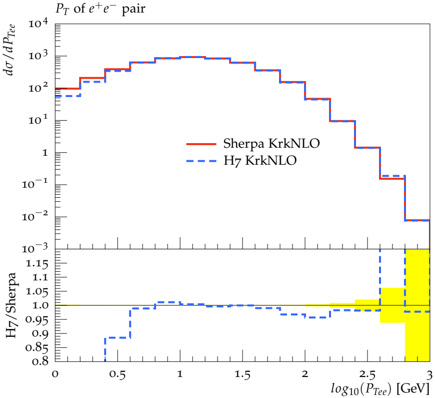
Drell-Yan
KrkNLO





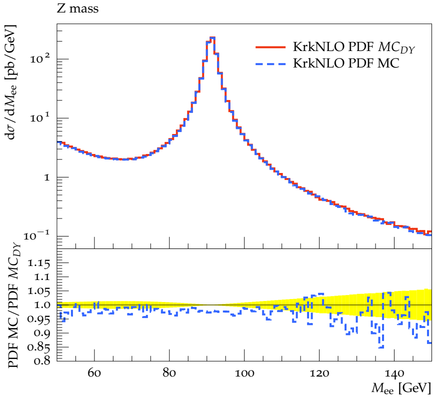
Drell-Yan
KrkNLO

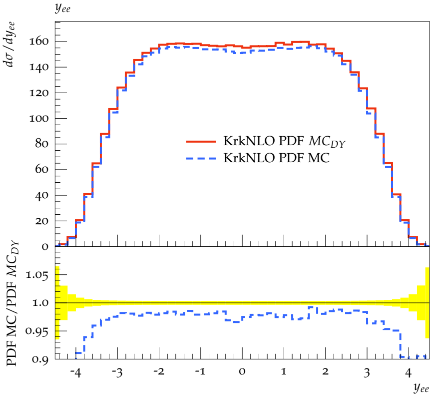




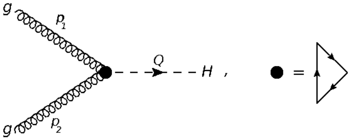
Drell-Yan

MCDY vs MC





Higgs



- Higgs boson production in gluon fusion
- Under the approximation $m_t \to \infty, m_q = 0$
- Compare to MCatNLO/Powheg as implented in Herwig 7

Higgs

As before, we get **simple** weights:

- Real
  - $g\ g \ \to\ H\ g$

$$W_R^{gg}(\alpha,\beta) = \frac{1 + z^4 + \alpha^4 + \beta^4}{1 + z^4 + (1-z)^4}$$

  - $g\ q \ \to\ H\ q$

$$W_R^{gq}(\alpha,\beta) = \frac{1 + \beta^2}{1 + (1-z)^2}$$

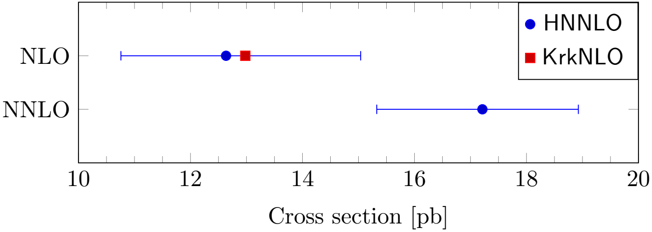
$$W_R^{qg}(\alpha,\beta) = W_R^{gq}(\beta,\alpha)$$

- Virtual+Soft, $W_{VS} = 1 + \Delta_{VS}$

$$\Delta_{VS}^{gg} = \frac{\alpha_s}{2\pi}\, C_A \left(\frac{4\pi^2}{3} + \frac{473}{36} - \frac{59}{18}\frac{T_f}{C_A} \right), \qquad \Delta_{VS}^{gq} = 0$$

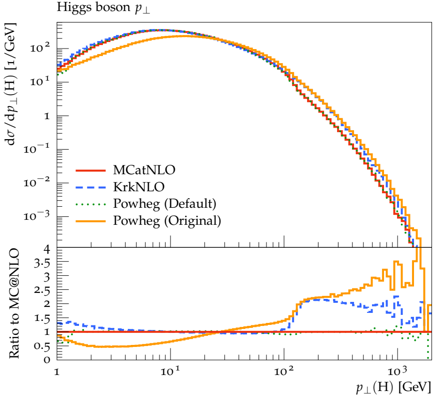
	MC@NLO	Powheg Default	Powheg Original	KrkNLO
σ_{tot} [pb]	12.712 (4)	12.697 (4)	12.717 (4)	12.979 (3)

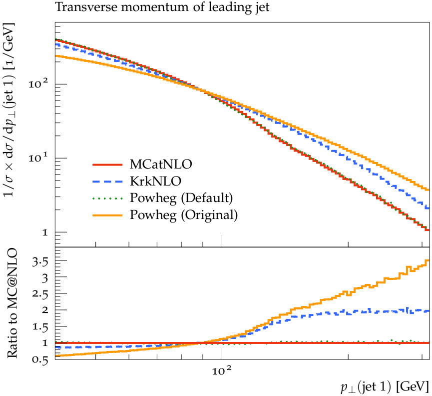
Total cross section for Higgs production via gluon-fusion



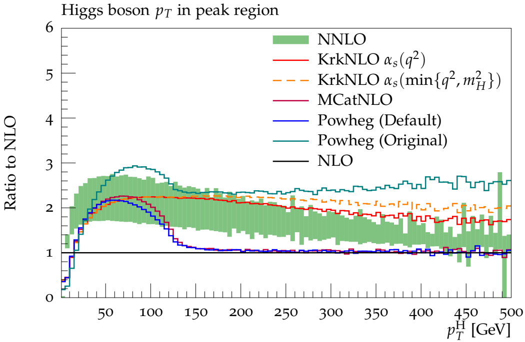
Higgs

Comparison of Matching methods





- Comparison of Powheg, MC@NLO and KrkNLO



- Higgs-boson p_T distribution from KrkNLO, MC@NLO, and Powheg, and fixed-order NNLO from HNNLO, normalised to fixed-order NLO.
- KrkNLO pT spectrum similar to the NNLO fixed order (similar observation for DY)

Recap

- KrkNLO method for NLO+PS matching
- MC Scheme PDFs
- Implementation of Drell-Yan and Higgs production in Herwig 7
- Validated against fixed-order, and compared to MC@NLO and Powheg results

Future Plans

- MC Scheme PDFs available at `krknlo.hepforge.org`
- Angular dependence for Z-decay
- KrkNLO code to be released as part of Herwig 7.1
- Correction of n-emissions
- More processes (More Drell-Yan type, di-boson)
- Eventually NNLO + NLO PS

Thanks!

krknlo.hepforge.org

Backup

K(z)

$$K_{gq}^{\mathrm{MC}}(z) = \frac{\alpha_s}{2\pi} C_F \left\{ \frac{1+(-z)^2}{z} \ln \frac{(1-z)^2}{z} + z \right\}$$

$$K_{gg}^{\mathrm{MC}}(z) = \frac{\alpha_s}{2\pi} C_A \left\{ 4\left[\frac{\ln(1-z)}{1-z}\right]_+ + 2\left[\frac{1}{z} - 2 + z(1-z)\right] \ln \frac{(1-z)^2}{z} \right.$$
$$\left. -2\frac{\ln z}{1-z} + -\delta(1-z)\left[\frac{\pi^2}{3} + \frac{341}{72} - \frac{59}{36}\frac{T_f}{C_A}\right] \right\}$$

$$K_{qq}^{\mathrm{MC}}(z) = \frac{\alpha_s}{2\pi} C_F \left\{ 4\left[\frac{\ln(1-z)}{1-z}\right]_+ + -(1+z)\ln\frac{(1-z)^2}{z} - 2\frac{\ln z}{1-z} \right.$$
$$\left. +(1-z) - \delta(1-z)\left[\frac{\pi^2}{3} + \frac{17}{4}\right] \right\}$$

$$K_{qg}^{\mathrm{MC}}(z) = \frac{\alpha_s}{2\pi} C T_R \left\{ \left[z^2 + (1-z)^2\right] \ln \frac{(1-z)^2}{z} + 2z(1-z) \right\}$$

$$K_{g\bar{q}}^{\mathrm{MC}}(z) = K_{gq}^{\mathrm{MC}}(z), \qquad K_{\bar{q}g}^{\mathrm{MC}}(z) = K_{qg}^{\mathrm{MC}}(z), \qquad K_{\bar{q}\bar{q}}^{\mathrm{MC}}(z) = K_{qq}^{\mathrm{MC}}(z)$$