Stefano Frixione

MC@NLO and MadFKS

Tool-readiness workshop, CERN, 30/3/2010

The basic idea

Take the NLO short-distance cross section, and remove from it all contributions that an MC gives to this perturbative order

The resulting subtracted cross section is finite, and can be unweighted. Hard partonic events obtained from unweighting are given to the MC as initial conditions (ie, act as hard subprocess) for the shower

Actual construction

The generating functional is:

$$\mathcal{F}_{\text{MC@NLO}} = \mathcal{F}^{(2\to n+1)}\, d\sigma^{(\mathbb{H})}_{\text{MC@NLO}} + \mathcal{F}^{(2\to n)}\, d\sigma^{(\mathbb{S})}_{\text{MC@NLO}}$$

with the two *finite* short-distance cross sections

$$d\sigma^{(\mathbb{H})}_{\text{MC@NLO}} = d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

$$d\sigma^{(\mathbb{S})}_{\text{MC@NLO}} = \int_{+1} d\phi_{n+1}\left(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

that feature the *MC subtraction terms*

$$\mathcal{M}^{(\text{MC})} = \mathcal{F}^{(2\to n)}\mathcal{M}^{(b)} + \mathcal{O}(\alpha_S^2\alpha_S^b)$$

Actual construction

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that feature the *MC subtraction terms*

$$\mathcal{M}^{(\text{MC})} = \mathcal{F}^{(2\to n)}\mathcal{M}^{(b)} + \mathcal{O}(\alpha_S^2\alpha_S^b)$$

- MC subtraction terms: one set of (process-independent) computations per PSMC
- NLO cross section written according to FKS subtraction formalism

MC@NLO 3.41 [Oct 09]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2030		7	7	×	$H_1H_2 \to tW^-/\bar{t}W^+ + X$
–2031		7	7	×	$H_1H_2 \to \bar{t}W^+ + X$
–2034		7	7	×	$H_1H_2 \to tW^- + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

MC@NLO 3.41 [Oct 09]

IPROC	IV	IL_1	IL_2	Spin	Process
–1706		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f'_i (\bar{t} \to)\bar{b}_l f_j f'_j + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f'_i / (\bar{t} \to)\bar{b}_k f_i f'_i + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f'_i + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f'_i + X$
–2030		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f'_i (W^- \to) f_j f'_j /$ $(\bar{t} \to)\bar{b}_k f_i f'_i (W^+ \to) f_j f'_j + X$
–2031		i	j	✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f'_i (W^+ \to) f_j f'_j + X$
–2034		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f'_i (W^- \to) f_j f'_j + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l_i^+ \nu_i (W^- \to) l_j^- \bar{\nu}_j + X$

`http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`

MC@NLO is now in GENSER (thanks to M. Kirsanov and A. Ribon)

The MC@NLO implementation for Z' hadroproduction by B. Fuks, M. Klasen, F. Ledroit, Q. Li and J. Morel (Nucl.Phys.B797:322-339,2008, arXiv:0711.0749) can be found at:

`http://lpsc.in2p3.fr/klasen/software`

Recent additions (after v3.3)

- All three single top production channels $(s,\, t,\, Wt)$ are now implemented, including spin correlations
- Off-shell effects (in the top mass) in $t\bar{t}$ production included
- Top hadronic decays with spin correlations included (and in W decays in Wt production). CKM effects in top decays
- Simpler form of the MC counterterms in the soft region, which allows one to simulate $b\bar{b}$ production at the LHC
- Much more flexible treatment of branching ratios and widths for top and W (in short: all can be given in input)
- Linking to LHAPDF upgraded. The assignment of Λ_{QCD} using LHAPDF inputs is now on solid grounds, with results virtually identical to those obtained with our PDF library

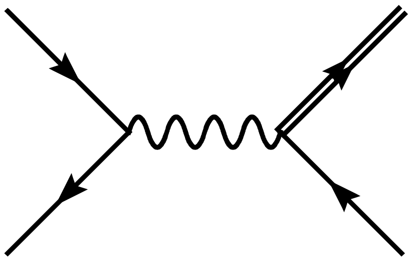
v3.4 $\longrightarrow$ v3.41

- Fixed a problem affecting top decays. In v3.4, the identities of decay products in n event samples of k events each could have been statistically not equivalent to those of one single event sample of $n \times k$ events. Relevant only for small k

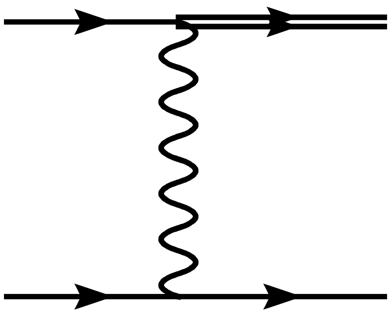
Thanks to Frank Filthaut for uncovering this problem and implementing a fix, and to Gia Khoriauli for testing v3.41

Single-top: production channels

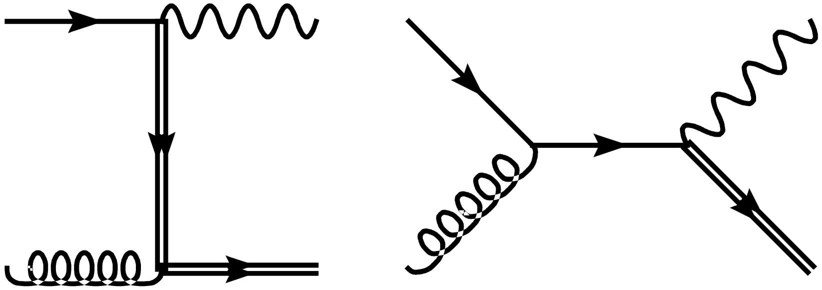
All are now included in v3.4



s channel



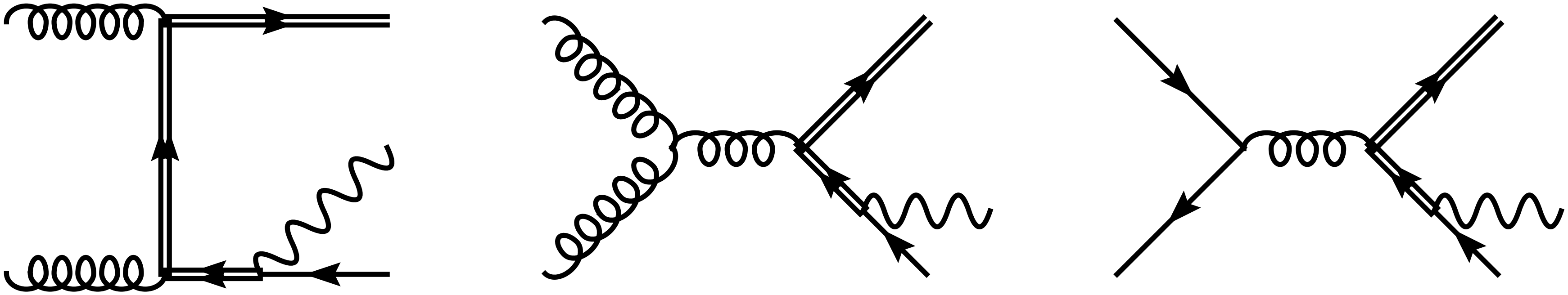
t channel



Wt channel

Wt production

...features very interesting peculiarities starting at NLO



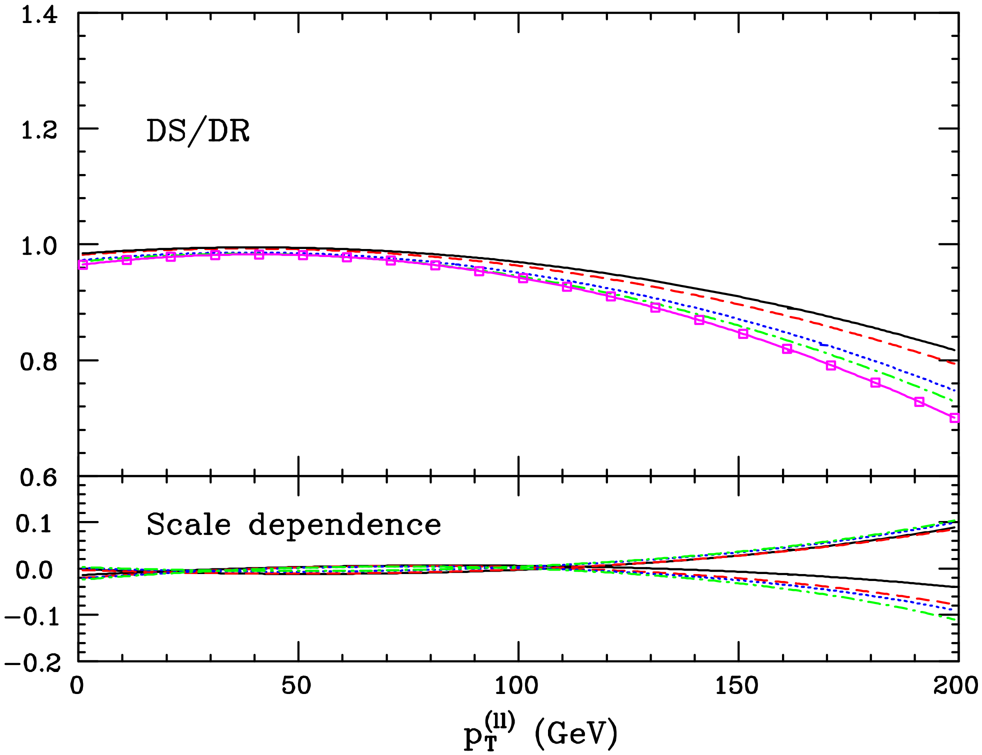
One just can't tell whether these diagrams are relevant to $t\bar{t}$ (with the t decay not drawn) or to Wt production

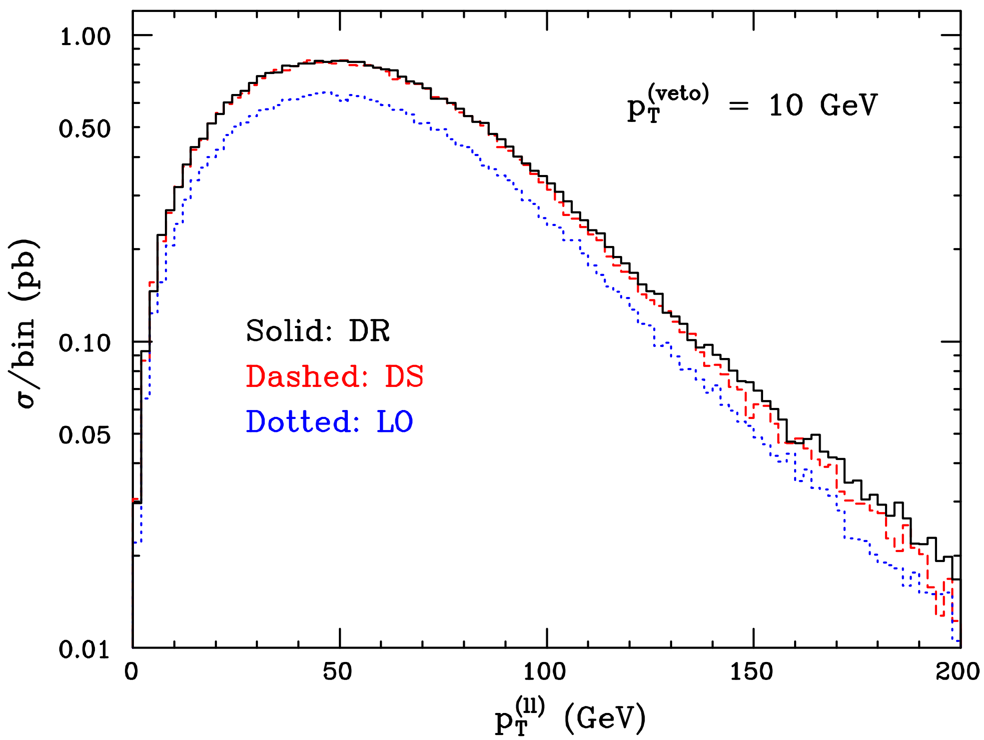
- $t\bar{t}$ and Wt production *interfere*. Wt has no *unambiguous definition*

- We implemented two definitions in MC@NLO, DR and DS, which do not make use of any final-state kinematic cuts

- If, after imposing the cuts of a given analysis, |DR-DS| is a small number, Wt production will have an operative meaning

Wt production





- Ambiguity is observable dependent
- This is a very tricky issue: take a look at JHEP 0807(2008)029 [arXiv:0805.3067] before starting (with MC@NLO or anything else). Phenomenology study: JHEP 0911(2009)074 [arXiv:0908.0631]

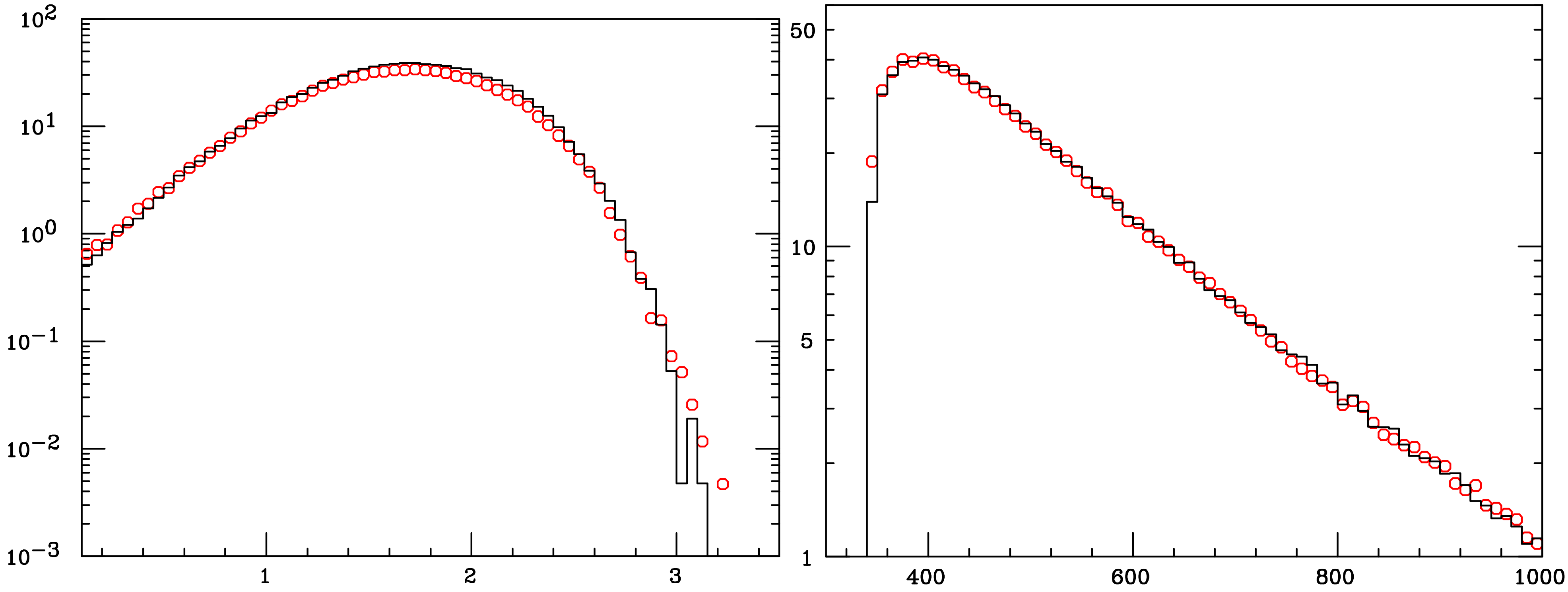
Next release: v3.5

- Core work: computation of the MC subtraction terms relevant to Herwig++
- Implications for v3.5: all processes available both with HW6 and with HW++

Work by F. Stoeckli, P. Torrielli, S. Latunde-Dada, B. Webber

- We planned on releasing the code in the next couple of weeks, but we are finding troubles with HW++ 2.4.2 – we are likely using weird inputs...
  We also need to write a proper documentation

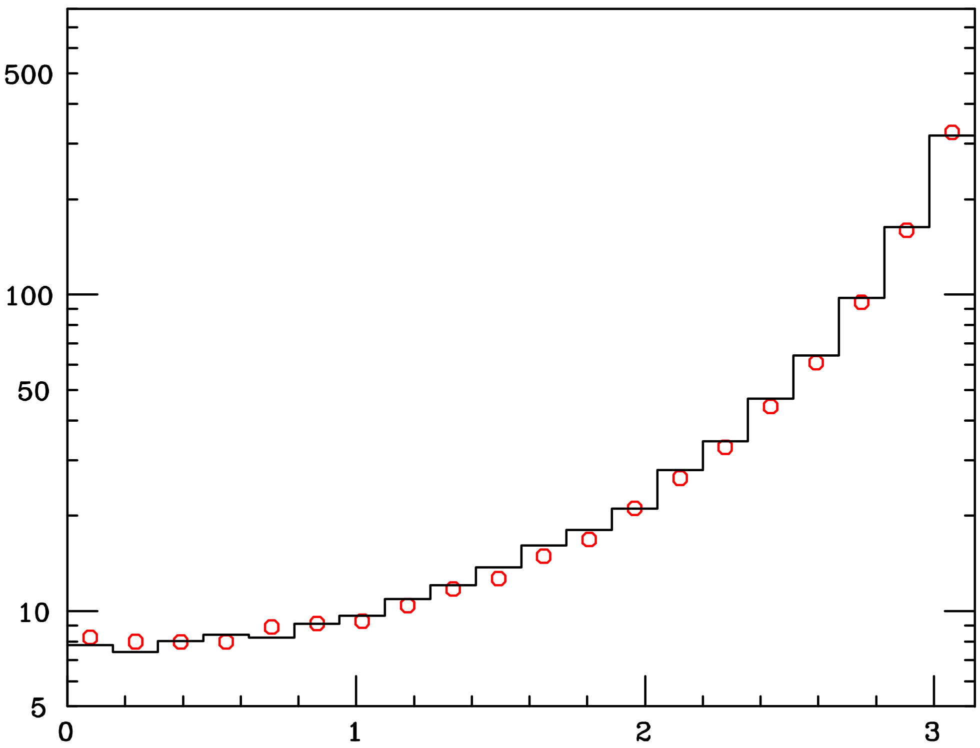
MC@NLO: HW6 vs HW++ ($t\bar{t}$)

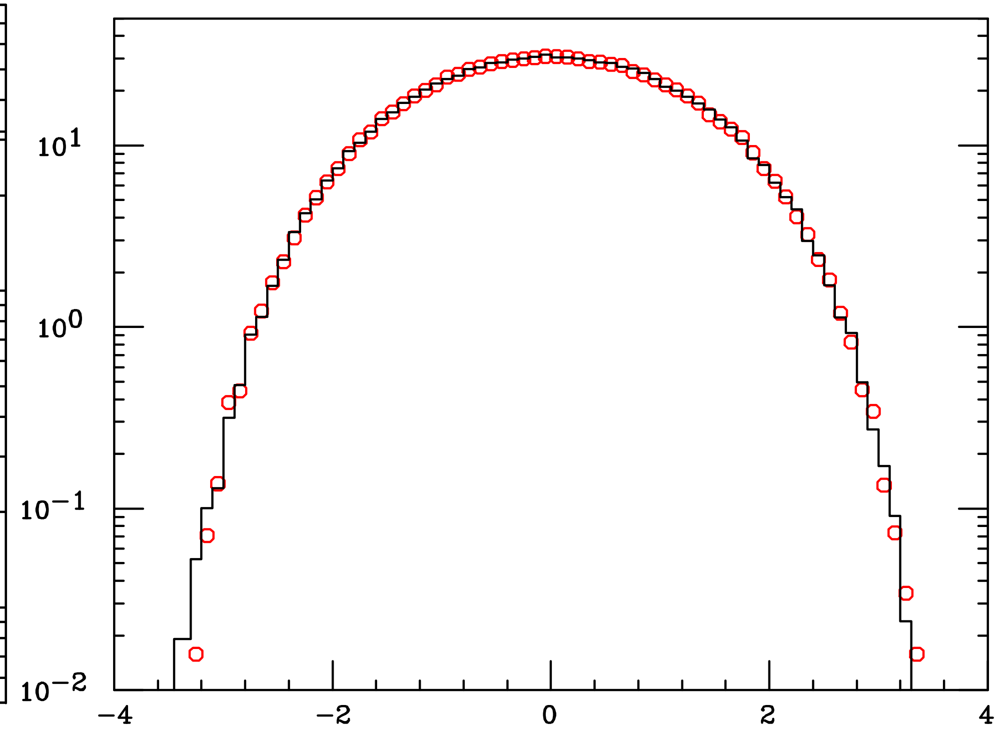


Histograms: HW6. Open circles: HW++

Left: pair p_T. Right: pair mass

MC@NLO: HW6 vs HW++ ($t\bar{t}$)

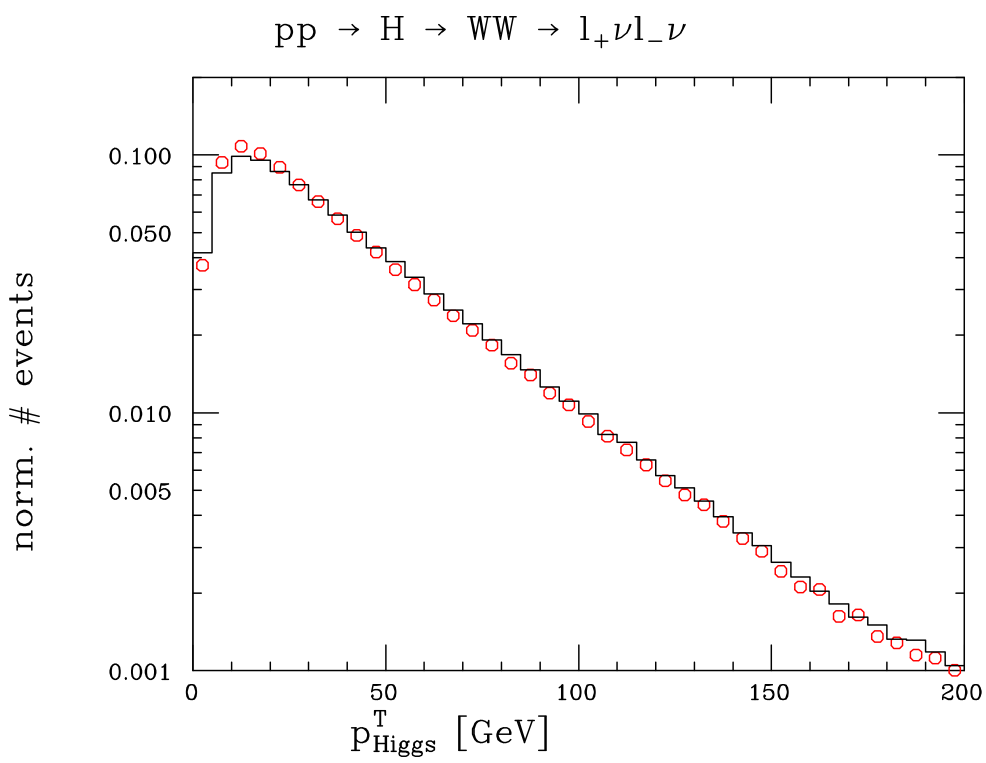


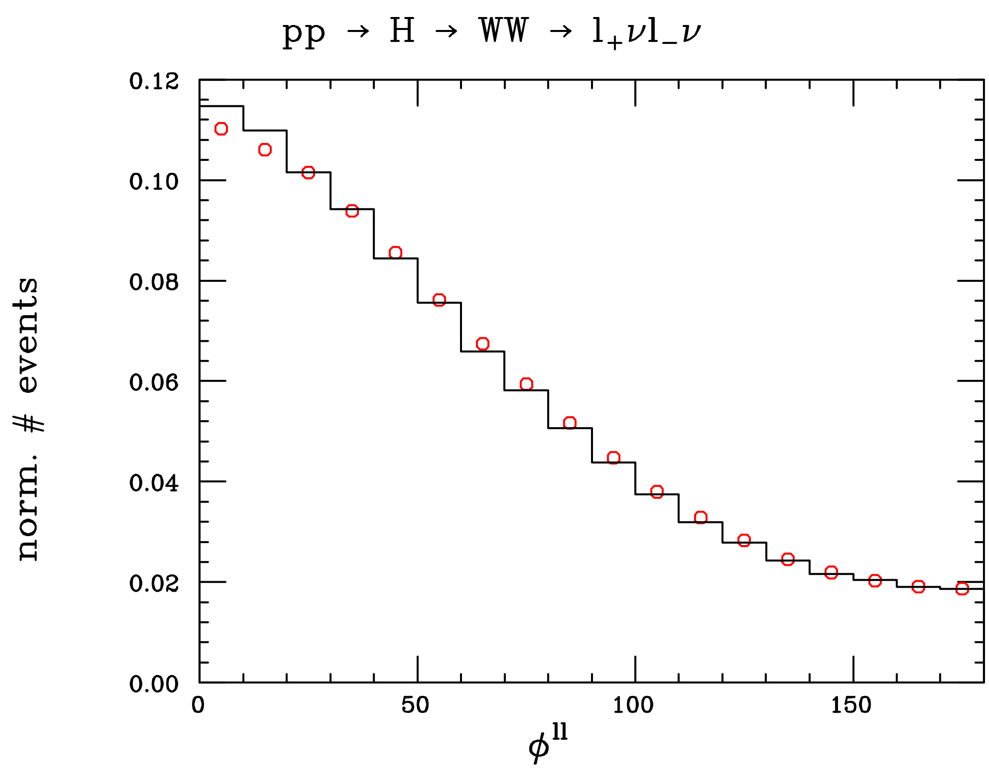


Histograms: HW6. Open circles: HW++

Left: pair $\Delta\phi$. Right: pair rapidity

MC@NLO: HW6 vs HW++ ($gg \to H \to WW$)

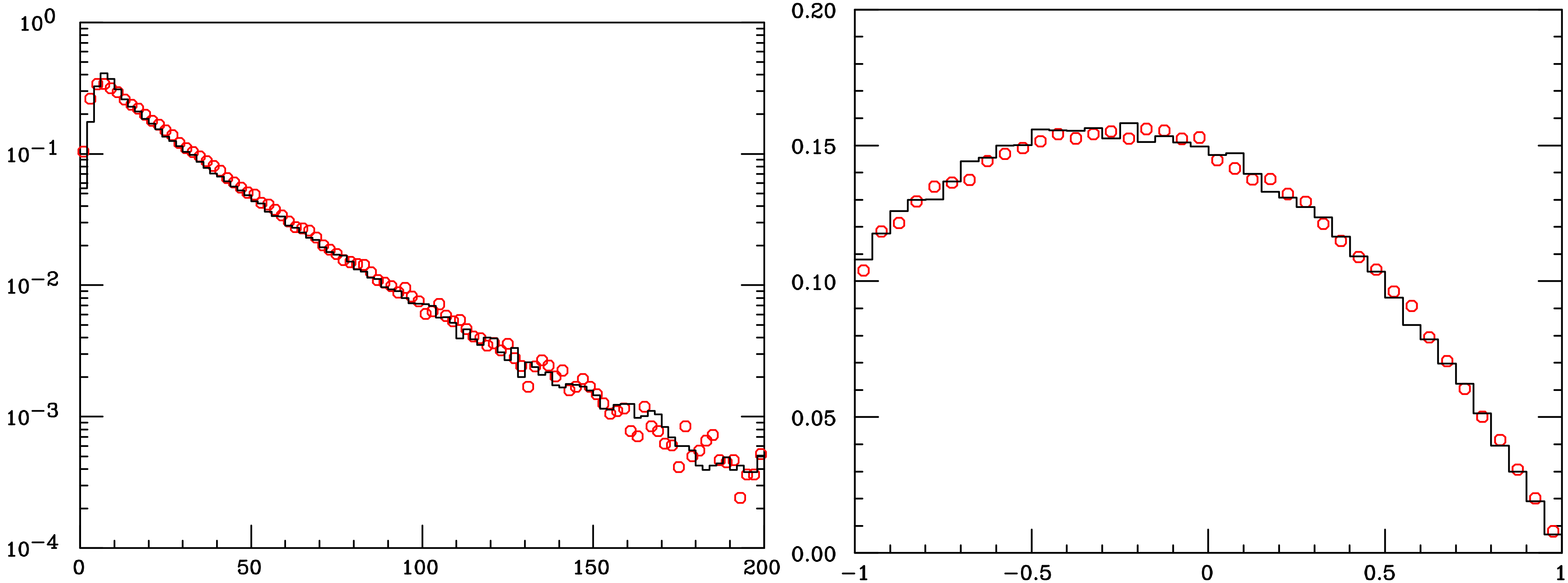




Histograms: HW6. Open circles: HW++

Left: Higgs p_T. Right: $\Delta\phi$ (charged leptons)

MC@NLO: HW6 vs HW$++$ (single-top t channel)



Histograms: HW6. Open circles: HW$++$

Left: p_T of top-hardest-jet pair. Right: lepton polarization angle

HW6 vs HW++

- Link either code via an input variable: in `MCatNLO.inputs`, set `MCMODE=HW6` or set `MCMODE=HWPP`
- In the case of standalone running: structure of directories enlarged

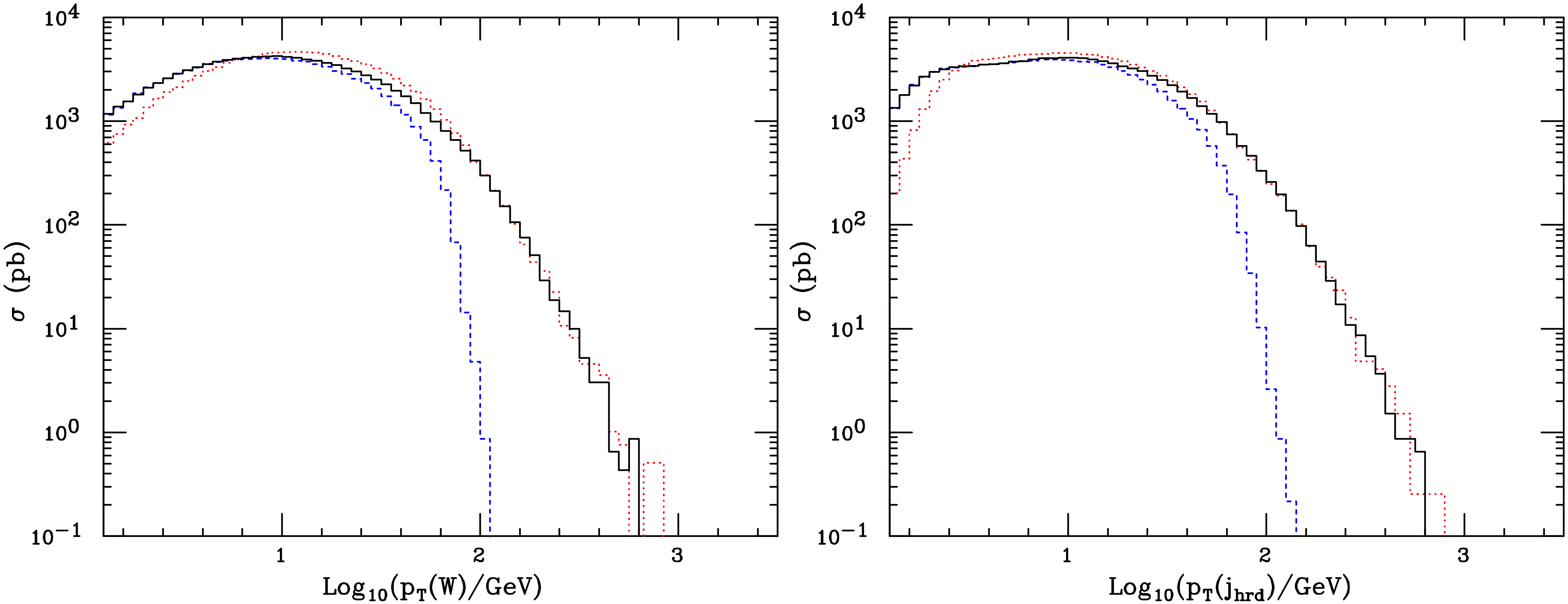
  Linux $\longrightarrow$ Linux, LinuxPP

  Source directory $\longrightarrow$ srcCommon, srcHerwig6, srcHerwigpp
  , HW6Analyzer, HWppAnalyzer
- Sample analysis files (both for HW6 and HW++) given, but as usual the user will have to write his/her own
- Technically: HW6 hard events still written in MC@NLO native format (requires interface, `mcatno_hwlhin.f`), HW++ ones written in LH format

PYTHIA

- Computations relevant to initial-state branchings MC subtraction terms worked out (P. Torrielli).
- Tested for virtuality-ordered shower
- Implemented for single-V and $gg \to H$ production

MC@NLO: PYTHIA (W production)

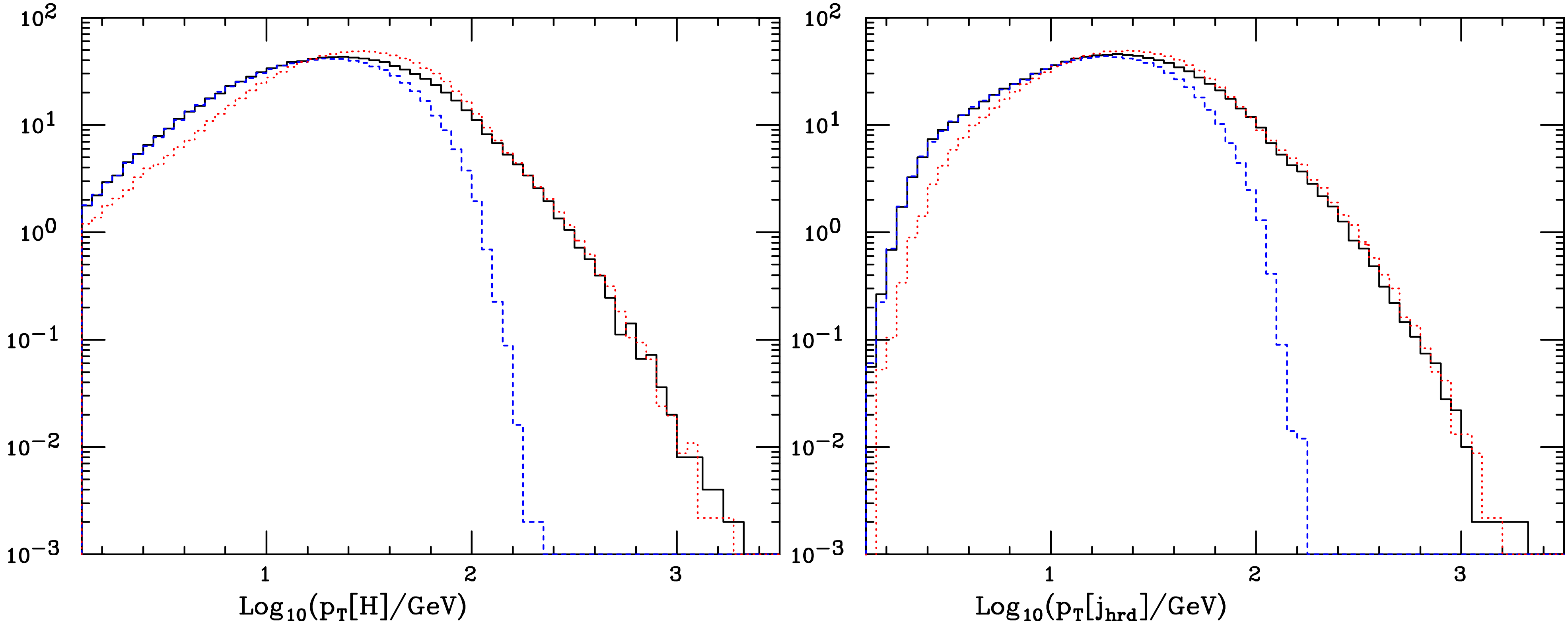


Solid: MC@NLO/PY; dashed: PY (no MEC); dotted: MC@NLO/HW6

Left: W p_T. Right: Hardest jet p_T

- Note: fraction of negative weights with PY is 0.5% (HW=8%)

MC@NLO: PYTHIA ($gg \to H$)



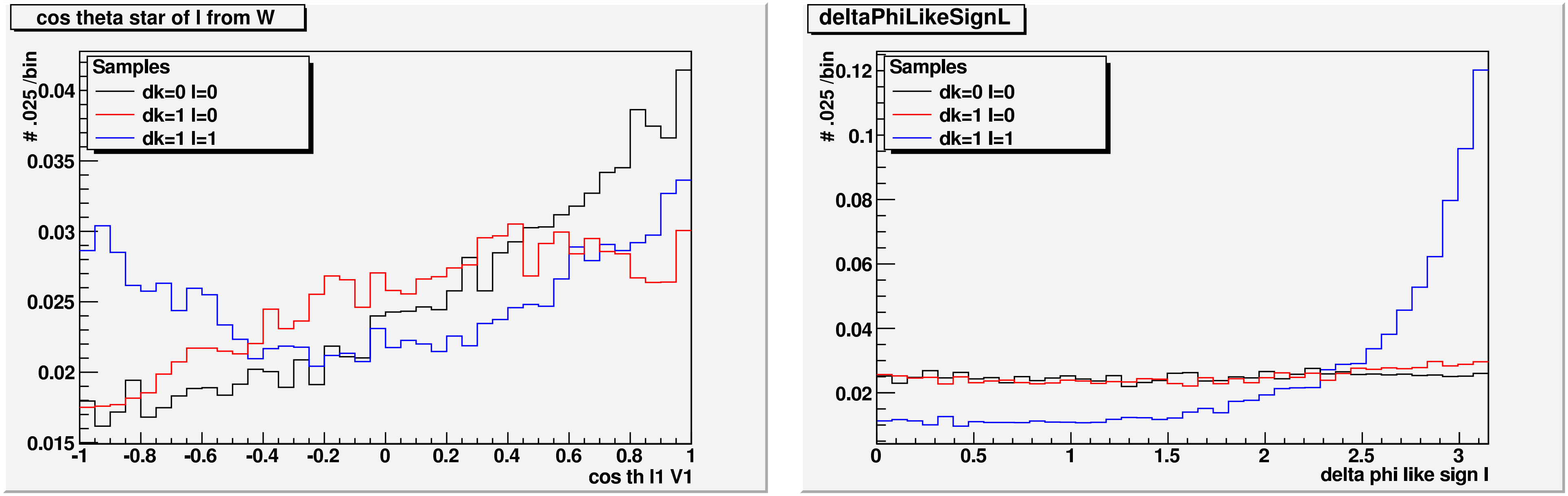
Solid: MC@NLO/PY; dashed: PY (no MEC); dotted: MC@NLO/HW6

Left: H p_T. Right: Hardest jet p_T

To be released with v3.51 (late spring?)

- Spin correlations and anomalous couplings for WZ production. Work by A. Oh.

WZ: spin corr and anomalous couplings

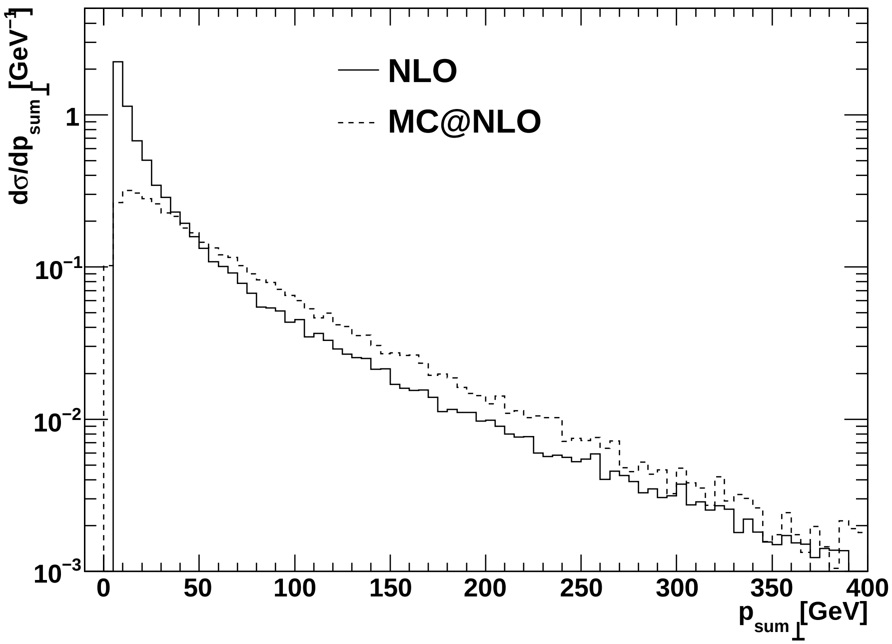


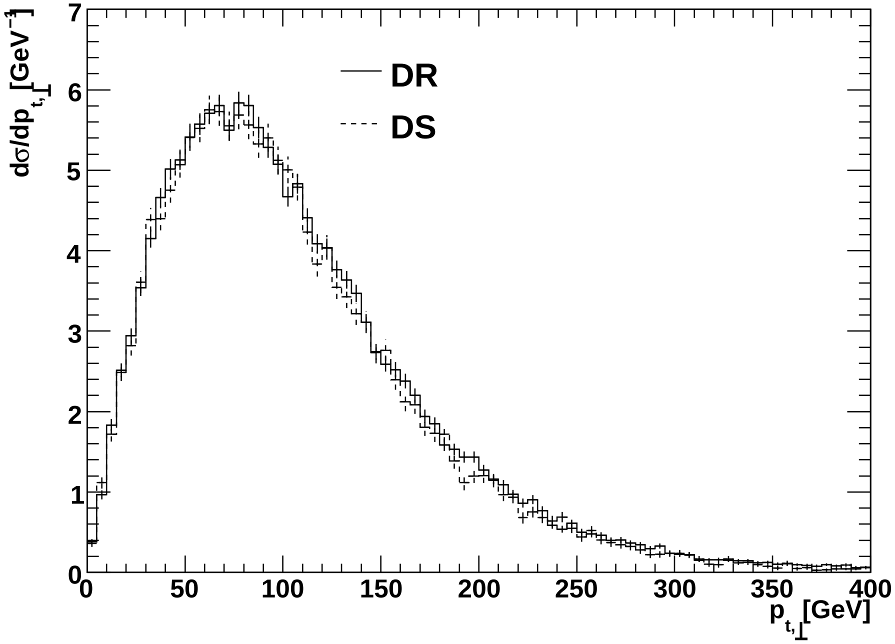
- Anom cpls as defined by Dixon, Kunszt, and Signer
- Actual values of couplings can be given *a posteriori*: the code outputs the ten coefficients that multiply all coupling combinations (ie, parametric representation of the cross section)

To be released with v3.51 (late spring?)

- Spin correlations and anomalous couplings for WZ production. Fully tested. Work by A. Oh.
- tH^-, $\bar{t}H^+$ in hadronic collisions, which has the same peculiarities of Wt production. To be released when spin correlations will be included (being done). Work by C. Weydert, M. Herquet, M. Klasen, E. Laenen, T. Plehn, G. Stavenga, C. White

tH production





- Implemented generic $V - A$ Htb vertex
- Plots for type-II two-Higgs-doublet-model, with $\tan\beta = 30$ and running b and t masses
- No definitions ambiguity for $m_H > m_t$

On MC@NLO code

Time for the inclusion of a new process is spent:

- 80% for the pure-NLO computation
- 15% for MC counterterms and LH-related code
- 5% debugging

The structure of the MC counterterms is modular

$$\mathcal{M}^{(\mathrm{MC})} = \mathcal{K}^{(\mathrm{MC})}\mathcal{M}^{(b)}$$

- This suggests to start automate the pure-NLO computations

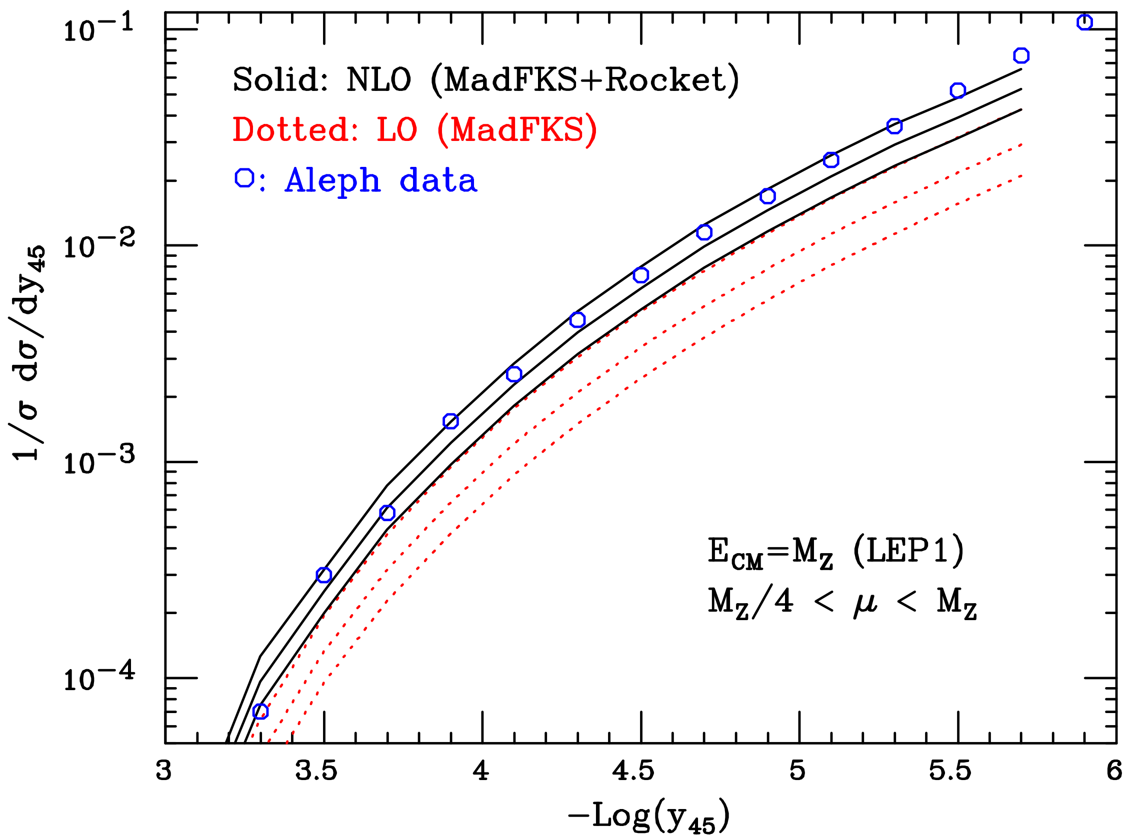
$\longrightarrow$ MadFKS

MadFKS (Frederix, Frixione, Maltoni, Stelzer)

The construction of all ingredients of the subtracted cross section, except for the finite part of the virtual contribution, is automated in MadFKS

- Effort justified by the significant progress made in recent years towards the automated computations of one-loop amplitudes
- Use of MadGraph is ubiquitous. MadFKS will become part of MadGraph/MadEvent release eventually
- MadFKS can compute QCD NLO corrections to any process resulting from a theory implemented in MadGraph – e.g. SUSY
- So far, virtual corrections obtained from BlackHat, Rocket, and several "private" codes written by various authors
- Both e^+e^- and hadron collisions cases fully tested now.

Test at high multiplicity: $e^+e^- \to 5$ jets



PRELIMINARY

Frederix, Frixione, Melnikov, Stenzel, Zanderighi

- Scale dependence: $+45\%$ -30% at LO, $\pm$ 20% at NLO
- Very large K-factors: 1.5 – 2
- Rocket and BlackHat agree pointwise
- Observable not ideal for fixed-order calculations (all jets are soft), so unclear whether α_s fit will be competitive

Technicalities

FKS subtraction

- Partition the phase-space into regions where one soft and one collinear singularity at most are present
- Different choices of integration variables in each of the regions of the partition – ideal from the point of view of importance sampling
- Naive scaling is n^2 (as opposed to n^3 of CS dipoles), but actually much better – for the hadroproduction of 1 zillion gluons we have 3 subtraction terms to compute

Technicalities

MadFKS

- From the user point of view, this is *identical* to MadGraph, except for the LH file with *finite* virtual corrections
- Automatic phase-space partition
- Automatic determination of subtraction terms – built on MadDipoles (Frederix, Greiner, Gehrmann)
- MadGraph computes all the tree-level matrix elements, and all the subtraction terms
- Multi-channeling sampling as for LO computations
- In-house implementation of CutTools (V. Hirschi, M. V. Garzelli, R. Frederix, R. Pittau), fully operational with MadGraph v5

Ongoing work on MadFKS

- We now have a version which allows one to Monte Carlo over helicity configurations – not fully tested yet
- Working out a version of FKS subtraction organised as a systematic $1/N_C$ expansion, which is easy to implement in MadFKS
- May want to integrate simultaneously processes that are topologically similar – best be done with MadGraph v5
- MC@NLO stuff $\longrightarrow$

Automation of MC@NLO

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- Black stuff: pure NLO, fully tested in MadFKS
- Red stuff: now available in MadFKS, being tested

Automation of MC@NLO

$$d\sigma^{(\mathbb{H})}_{\mathrm{MC@NLO}} = d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\mathrm{MC})}(\phi_{n+1})\right)$$

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- Black stuff: pure NLO, fully tested in MadFKS
- Red stuff: now available in MadFKS, being tested

Automation of MC subtraction terms

- Branching structure is for free: FKS subtraction is based on a collinear picture, so we can exploit what done for NLO
- Automatic determination of colour partners
- Automatic computation of leading-N_C matrix elements
- Works also when MC-ing over helicities

Outlook

MC@NLO

- Release of v3.5 (HW6 and HW$++$) as soon as documentation is ready (and issues with HW$++$ 2.4.2 sorted out)
- $H^{\pm}t$ and WZ with anomalous couplings later in spring
- First results with Pythia

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MadFKS

- NLO cross section computations with MadFKS thoroughly tested for $e^{+}e^{-}$ and hadronic collisions
- Will start now to do LHC phenomenology but need to figure out priorities – finite virtual may not always easy to get

Outlook

Automated MC@NLO

- The code is ready, but we have just tested the integration of the short-distance cross sections for a few cases (up to four jets in e^+e^-)
- We shall be able to assess its performances in the next couple of months

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Thanks to all friends who have been working on these projects over the past few years