NLO efforts in HERWIG++

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Loopfest–Radcor 2015

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- Exclusive event generation in particle collisions at had–had, had–lep and lep–lep colliders
- HERWIG++ is written in C++ and based on THEPEG [http://home.thep.lu.se/~leif/ThePEG/]
  - Toolkit for HEP Event Generation, incl. interface to LHAPDF
- Currently newest release: HERWIG++ 2.7.1
  - Hard process and parton shower Monte Carlo
    - Several built–in LO and NLO hard matrix elements
    - LHE file input
    - Angular ordered parton shower
    - Dipole shower
    - Powheg matched / matrix element corrected (largely hand made or semi–automated)
    - Decays of heavy resonances (incl. spin correlations)
  - Simulation of hadronization
    - Cluster hadronization model
    - Color reconnection
    - Decays
  - Simulation of MPI and underlying event
  - BSM machinery: Built–in processes as well as UFO model file input

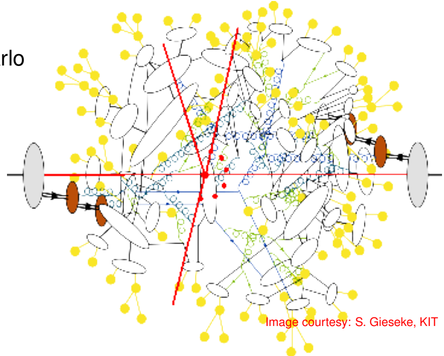

Image courtesy: S. Gieseke, KIT

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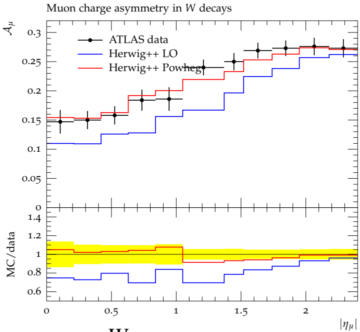
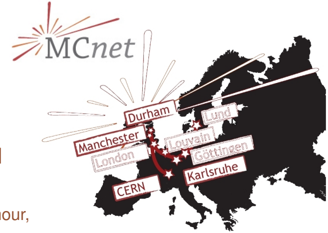


$pp \to W$
[K. Hamilton et al., JHEP 0904 (2009) 116]

- HERWIG++ $\in$ MCnet (Marie Curie initial training network)
- Distributed over several institutes
  - IPPP (Durham) [D. Grellscheid, P. Richardson, S. Plätzer, P. Schichtel, A. Wilcock]
  - ITP (KIT, Karlsruhe) [J. Bellm, F. Loshaj, S. Gieseke, CR; assoc.: N. Fischer (now Monash University), D. Rauch (now DESY Hamburg)]
  - CERN Theory Group [A. Papaefstathiou, A. Siodmok]
  - Manchester Particle Physics Group (Manchester U) [G. Nail, M. Seymour, J. Da Silva]
  - University of Cambridge [B. Webber]



- Focus in the various groups
  - Durham: Parton showers, NLO development; Mass effects; BSM, Higgs physics; Spin correlations; Hadronization
  - Karlsruhe: Parton showers, NLO development; Mass effects; Hadronization and soft physics
  - CERN: Hadronization and soft physics; BSM, Higgs physics
  - Manchester: Mass effects (initial state); Soft physics (diffraction)

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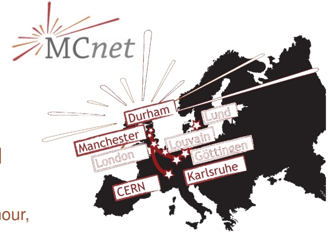


- This talk: NLO efforts in and outlook on the upcoming new release of HERWIG++
  - Automated matching/merging requires full control of fixed order input
    Change of paradigm – Need for a fully integrated framework
  - MATCHBOX forms the basis for the automated NLO capabilities of HERWIG++
    - HERWIG++ 2.7.1 includes a β–version of the MATCHBOX framework [Plätzer, Gieseke '12]
    - Turn NLO QCD calculations to parton shower matched calculations
    - Automated process setup for the underlying NLO QCD calculations
    - Implementation of the CS dipole subtraction method
    - Interface to the two shower variants in Herwig++
    - Interface to the necessary matrix elements
    - Automated diagram based multi–channel phase space sampling and adaptive phase space integration

- Event generators aim at exclusive final states with $O(1000)$ particles.
- Fixed order calculations can only do a limited number of legs. State-of-the-art: $O(10)$.
- Logarithmic enhancements in the soft/collinear regions of phase space.
  Need to be resummed to all orders in α_s.

- Fixed order matrix elements (ME)
  - ✓ Exact results at a certain fixed order, especially for large angle / hard radiation.
  - ✗ No all–order resummation of the large logarithmic enhancements in the soft/collinear regions.

- Parton showers (PS)
  - ✓ Generate a large amount of partons, due to multiple emissions in the soft/collinear approximation. Evolving an inclusive cross section at a hard scale into an exclusive final state at a lower cut–off scale.
  - ✓ Approximate the matrix element to “all” orders in the soft/collinear regions, i.e. resummation at leading log (next–to–leading log) accuracy.
  - ✗ The hard regions of phase space are naturally described badly.

- Matching/Merging
  - Combine PS and ME by correcting (or replacing) the hardest emission(s) of the PS.
  - The more MEs get involved, the better. Hard regions by the MEs, soft regions by the PS.
  - PS and MEs combined show overlapping contributions $\rightarrow$ double counting! ✗
    E.g. in the NLO real contribution to a specific inclusive calculation.
  - Matching and merging algorithms: Remove the double counting by deriving formulas for auxilliary cross sections, or algorithms to combine multiple inclusive calculations, upon which the shower can be applied without leading to double counting.

- Most NLO QCD calculations nowadays use the subtraction method to regularize the soft/collinear divergencies between the two different phase spaces of the virtual and real corrections:
  - Dipole subtraction
    Implemented in MATCHBOX
  - Antenna subtraction
  - Residue subtraction
  - Nagy–Soper subtraction
- The last years have witnessed a tremendous progress in one–loop calculations.
  The Les Houches NLO wishlist of 2005/2007 “retired” about two years ago.

  This “NLO revolution” has given birth to many automated programs, which are also used as *one–loop providers (OLPs)* to MC event generators, e.g.
  - BLACKHAT
    talk by [D. Maitre]
  - NJET
  - NLOX
  - VBFNLO
  - MG5_AMC@NLO
    talks by [V. Hirschi, M. Zaro]
  - OPENLOOPS
    talks by [J. Lindert, P. Maierhöfer]
  - GOSAM
    talks by [N. Greiner, G. Ossola]
  - RECOLA
    talks by [A. Denner, S. Uccirati]
  - Idea: Let the MC event generator manage the computation (process setup, subtraction, phase space integration, ...) and use the OLPs for ME input, as for example suggested in the BLHA(2) accord.
- All ingredients for matching and merging of multi–parton NLO fixed order calculations to parton showers are therefore in place.

- Recursively applying the parton shower operator generates higher orders
  See also talk by [N. Fischer]

$$\mathsf{PS}[Q^2,\mu_{\mathsf{IR}}^2,\Phi_n,O] = \Delta(Q^2,\mu_{\mathsf{IR}}^2,\Phi_n)O_n + \int_{\mu_{\mathsf{IR}}^2}^{Q^2} \mathsf{d}\mathcal{P}(q^2)\Delta(Q^2,q^2,\Phi_n)\mathsf{PS}[q^2,\mu_{\mathsf{IR}}^2,\Phi_{n+1},O]$$

$$\text{w/} \qquad \Delta(Q^2,\mu_{\mathsf{IR}}^2,\Phi_n) = \exp\left[-\int_{\mu_{\mathsf{IR}}^2}^{Q^2} \mathsf{d}\mathcal{P}(q^2)\right] = 1 - \int_{\mu_{\mathsf{IR}}^2}^{Q^2} \mathsf{d}\mathcal{P}(q^2) + \mathcal{O}(\alpha_s^2)$$

- Naive combination of NLO

$$O_{\mathsf{NLO}} = \int \mathsf{d}\Phi_n\left(\mathcal{B}+\bar{\mathcal{V}}\right)O_n + \int \mathsf{d}\Phi_{n+1}\left(\mathcal{R}O_n - \mathcal{A}O_{n+1}\right) \;, \quad \bar{\mathcal{V}} = \mathcal{V} + \int d\Phi_1\mathcal{A}$$

and PS yields thus (up to NLO)

$$O_{\mathsf{NLO+PS}}^{\mathsf{unmatched}} = \int \mathsf{d}\Phi_n\left(\mathcal{B}+\bar{\mathcal{V}}\right)O_n + \int \mathsf{d}\Phi_n\,\mathcal{B}\int_{\mu_{\mathsf{IR}}^2}^{Q^2} \mathsf{d}\mathcal{P}(q^2)\left(O_{n+1} - O_n\right) + \int \mathsf{d}\Phi_{n+1}\left(\mathcal{R}O_{n+1} - \mathcal{A}O_n\right)$$

- Double–counting between PS & real emission and PS & virtual contribution
- Total inclusive cross section unaffected (replace O_n and O_{n+1} by 1)
- Matching: Restore correct $\mathcal{O}(\alpha_s^{F+1})$ expression w/ F the Born α_s–order

- Subtracting the PS contribution yields a matched (auxilliary) cross section

$$O_{\text{NLO}}^{\text{matched}} = \int \mathrm{d}\Phi_n \left(\mathcal{B}+\bar{\mathcal{V}}\right) O_n - \int \mathrm{d}\Phi_n \, \mathcal{B} \int_{\mu_{\text{IR}}^2}^{Q^2} \mathrm{d}\mathcal{P}(q^2) \left(O_{n+1} - O_n\right) + \int \mathrm{d}\Phi_{n+1} \left(\mathcal{R} O_{n+1} - \mathcal{A} O_n\right)$$

and rearranging wrt O_n and O_{n+1} yields S– and H–events:

$$O_{\text{NLO}}^{\text{matched}} = \left[\int \mathrm{d}\Phi_n \left(\mathcal{B}+\bar{\mathcal{V}}\right) - \int \mathrm{d}\Phi_{n+1} \mathcal{A} + \int \mathrm{d}\Phi_n \, \mathcal{B} \int_{\mu_{\text{IR}}^2}^{Q^2} \mathrm{d}\mathcal{P}(q^2)\right] O_n$$

$$+ \left[\int \mathrm{d}\Phi_{n+1} \mathcal{R} - \int \mathrm{d}\Phi_n \, \mathcal{B} \int_{\mu_{\text{IR}}^2}^{Q^2} \mathrm{d}\mathcal{P}(q^2)\right] O_{n+1}$$

- S– and H–events are obviously not separately finite. Add extra term (bridge cross section) below the shower cut–off:

$$\int \mathrm{d}\Phi_{n+1} \mathcal{A}_{\text{bridge}}(\Phi_{n+1}) \Theta(\mu_{\text{IR}}^2 - q^2) \left(O_n - O_{n+1}\right)$$

- Only adds power corrections for IR safe observables. Thus the resummation of large logarithms is not destroyed
- Subtract real–emission sing. in the $n+1$–parton bin and sing. of $\mathcal{A}$ in the n–parton bin
- MC@NLO–like: $\mathcal{A}_{\text{bridge}} = \mathcal{R}$, $\mathcal{A} = \mathcal{B}\mathcal{P}$
- Weights of H–events may become negative.
- Also built in POWHEG–like matching. “MEC” to reproduce real emission correctly by the first (hardest emission). The angular ordered shower has to be vetoed and truncated for this.

- In HERWIG++/MATCHBOX choose $\mathcal{A}_{\text{bridge}} = \mathcal{A} = \mathcal{A}_{\text{CS}}$:

$$O_{\text{NLO}}^{\text{matched}} = \Bigg[\overbrace{\int d\Phi_n \left(\mathcal{B}+\bar{\mathcal{V}}\right)}^{\substack{A_n^{(0)},\ A_n^{(1)} \\ |A_n^{(0)}|^2,\ \langle A_n^{(0)}|A_n^{(1)}\rangle,\ |A_n^{(0)}|_{ij}^2}} + \overbrace{\int d\Phi_n \mathcal{B} \int_{\mu_{IR}^2}^{Q^2} d\mathcal{P}(q^2)}^{\substack{P(\tilde{q}),D(p_\perp) \\ R_{MEC}(p_\perp)}} - \overbrace{\int d\Phi_{n+1} \mathcal{A}_{\text{CS}} \Theta(q^2-\mu_{IR}^2)}^{\substack{A_n^{(0)} \\ |A_n^{(0)}|_{ij}^2}} \Bigg] O_n$$

$$+ \Bigg[\underbrace{\int d\Phi_{n+1} \mathcal{R}}_{\substack{A_{n+1}^{(0)} \\ |A_{n+1}^{(0)}|^2}} - \underbrace{\int d\Phi_n \mathcal{B} \int_{\mu_{IR}^2}^{Q^2} d\mathcal{P}\left(q^2\right)}_{\substack{P(\tilde{q}),D(p_\perp) \\ R_{MEC}(p_\perp)}} - \underbrace{\int d\Phi_{n+1} \mathcal{A}_{\text{CS}} \Theta\left(\mu_{IR}^2-q^2\right)}_{\substack{A_n^{(0)} \\ |A_n^{(0)}|_{ij}^2}} \Bigg] O_{n+1}$$

- Interfaces at amplitude level
  - Spinor helicity library and caching facilities [S. Plätzer]
  - Color bases provided, including interface to COLORFULL [M. Sjödahl, S. Plätzer]
  - Some built–in (one–loop) helicity amplitudes
  - In–house calculations, i.e. parts of HJETS++ [F. Campanario, T. Figy, S. Plätzer, M. Sjödahl]
  - MG5_AMC@NLO [MADGRAPH & J. Bellm, S. Gieseke, S. Plätzer, A. Wilcock]

- Interfaces at matrix element level
  - Dedicated interfaces [HEJ & S. Plätzer; NLOJET++ & J. Kotanski, J. Katzy, S. Plätzer]
  - BLHA(2) [GOSAM & J. Bellm, S. Gieseke, S. Plätzer, D. Rauch, CR; NJET & S. Plätzer; OPENLOOPS & J. Bellm, S. Gieseke; VBFNLO & K. Arnold, S. Gieseke, S. Plätzer, M. Rauch]
- Shower plugins: Angular ordered $P(\tilde{q})$, Dipole shower $D(p_\perp)$, MEC $R_{MEC}(p_\perp)$

- In HERWIG++/MATCHBOX choose $\mathcal{A}_{\text{bridge}} = \mathcal{A} = \mathcal{A}_{\text{CS}}$:

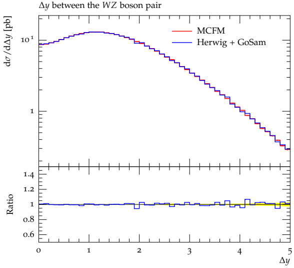
$$
\begin{aligned}
O_{\text{NLO}}^{\text{matched}} = & \left[\overbrace{\int d\Phi_n \left(\mathcal{B} + \bar{\mathcal{V}}\right)}^{\substack{A_n^{(0)},\ A_n^{(1)} \\ |A_n^{(0)}|^2,\ \langle A_n^{(0)}|A_n^{(1)}\rangle,\ |A_n^{(0)}|^2_{ij}}} + \overbrace{\int d\Phi_n \mathcal{B} \int_{\mu_{IR}^2}^{Q^2} d\mathcal{P}(q^2)}^{\substack{P(\tilde{q}), D(p_\perp) \\ R_{MEC}(p_\perp)}} - \overbrace{\int d\Phi_{n+1} \mathcal{A}_{\text{CS}} \Theta(q^2 - \mu_{IR}^2)}^{\substack{A_n^{(0)} \\ |A_n^{(0)}|^2_{ij}}} \right] O_n \\
& + \left[\underbrace{\int d\Phi_{n+1} \mathcal{R}}_{\substack{A_{n+1}^{(0)} \\ |A_{n+1}^{(0)}|^2}} - \underbrace{\int d\Phi_n \mathcal{B} \int_{\mu_{IR}^2}^{Q^2} d\mathcal{P}\left(q^2\right)}_{\substack{P(\tilde{q}), D(p_\perp) \\ R_{MEC}(p_\perp)}} - \underbrace{\int d\Phi_{n+1} \mathcal{A}_{\text{CS}} \Theta\left(\mu_{IR}^2 - q^2\right)}_{\substack{A_n^{(0)} \\ |A_n^{(0)}|^2_{ij}}} \right] O_{n+1}
\end{aligned}
$$

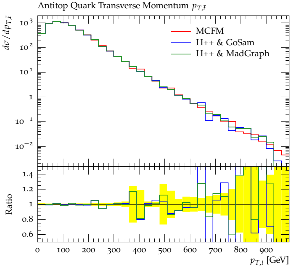
- Since Matchbox–β major improvements have been made
  - Interfaces to various external matrix element providers
  - Fully automated NLO matching (MC@NLO, POWHEG)
  - Unitarized NLO merging (in validation phase) [J. Bellm, S. Gieseke, S. Plätzer]
  - Major improvements to the multi–channel phase space sampling and integration [CELLGRID sampler: J. Bellm, S. Plätzer; MONACO adaption: J. Bellm, S. Plätzer, M. Rauch]
  - α–parametrized dipole subtraction (for massless) [J. Bellm, S. Plätzer]
  - Massive CDST dipole subtaction and mass effects [J. Bellm, S. Plätzer, D. Rauch, CR, M. Stoll]
  - Massive dipole kernels in the dipole shower; mass effects in POWHEG [S. Plätzer, P. Richardson, A. Wilcock]

Matchbox validation fixed order

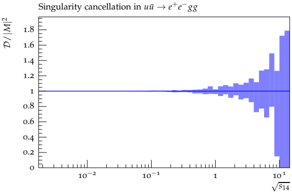
Plots by N. Fischer, D. Rauch
J. Bellm, S. Plätzer

- Extensive validation against e.g. MCFM

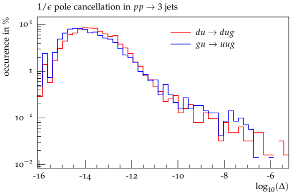




- Various internal cross checks: Subtraction checks, pole cancellation.

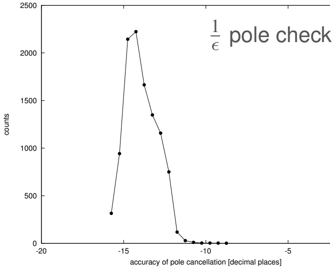


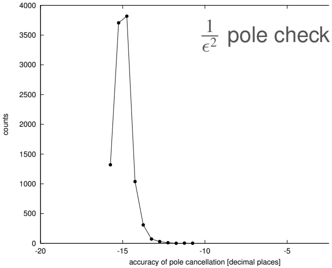
$pp \to Z + \text{jet}$ (GoSam)

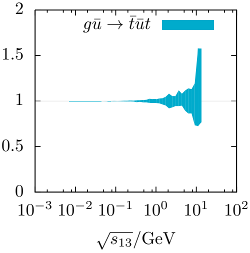


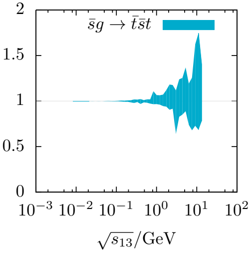
$pp \to 3$ jets (NJet)

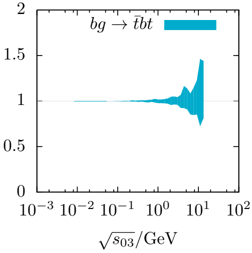
- Cross checking pole cancellation and subtraction in $pp \to t\bar{t}$ (GoSam)











- Necessary dependencies
  - THEPEG (LHAPDF, HEPMC, RIVET), FASTJET, BOOST
- OLP dependencies (if desired)
  - GOSAM 2.0.2, MG5_AMC@NLO 2.3.0, OPENLOOPS 1.1.1, NJET 2.0.0, VBFNLO, ...
- Installing HERWIG++ is as easy as it gets: Get it from https://herwig.hepforge.org/, then
  - `./configure --prefix=/Your-Desired-Installation-Path/ --with-thepeg=/Path-To-ThePEG-Installation/ --with-fastjet=/.../ --with-gosam=/.../ --with-madgraph=/.../ --with-openloops=/.../ --with-njet=/.../ --with-vbfnlo=/.../`
  - `make && make install`
- Using HERWIG++
  - Define your input card / “infile”, e.g. `LHC-Matchbox.in`
  - Read: `Herwig++ read LHC-Matchbox.in` $\longrightarrow$ Returns the generator run card `LHC-Matchbox.run`
    Builds the MEs and performs the grid adaption for the phase space sampling per sub–process
    The grid adaption can also be done in parallel
  - Run: `Herwig++ run LHC-Matchbox.run -N 1000000` $\longrightarrow$ Produces 1M events as HEPMC, RIVET histograms, ...
- The “infile”
  - HERWIG++ is/was known to have complicated input cards
  - With the new release HERWIG++ will receive a face lifting:
    - Based on MATCHBOX infiles
    - New: Snippet structure, i.e. pre–prepared infile snippets to contain a specific set of commands for a specific task

Choose collider type and energy

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Which hard process do you want?

Choose order in α_S and α_{EW}, choose process

Have your favourite choice of ME provider!

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```

HERWIG++/MATCHBOX example input file $pp \to t\bar{t}$

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read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Choose cuts and scale

More examples will be found in the documentation

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in
```

Match on two choices of shower algorithms

MC@NLO or Powheg on angular ordered or dipole shower

Simple MEC also possible

Fixed order runs at LO or NLO are also an option!

Just pick your favourite process, or give us your favourite ME

```
## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

E.g. `MuDown.in`

```
cd /Herwig/MatrixElements/Matchbox
set Factory:RenormalizationScaleFactor 0.5
set Factory:FactorizationScaleFactor 0.5
set MEMatching:RenormalizationScaleFactor 0.5
set MEMatching:FactorizationScaleFactor 0.5
cd /Herwig/Shower
set ShowerHandler:RenormalizationScaleFactor 0.5
set ShowerHandler:FactorizationScaleFactor 0.5
cd /Herwig/DipoleShower
set DipoleShowerHandler:RenormalizationScaleFactor 0.5
set DipoleShowerHandler:FactorizationScaleFactor 0.5
```

Scale variations on hard scales
and
shower scales!

HERWIG++/MATCHBOX example input file $pp \to t\bar{t}$

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Which flavour(s)?
Which PDF set?
Other choices are also possible

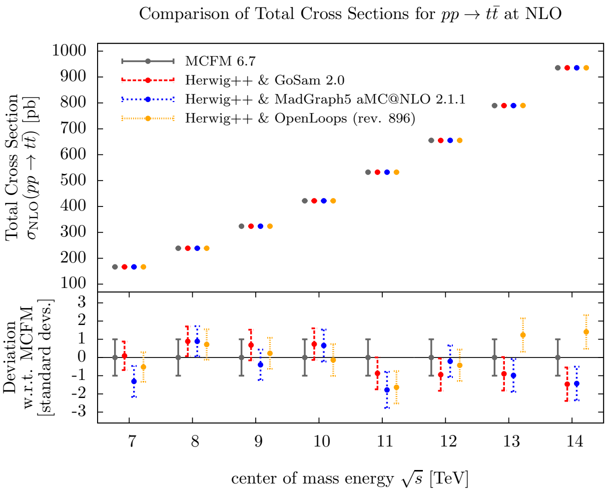
```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Which RIVET analyses?

HEPMC output also possible

built–in analyses also possible

Plots by D. Rauch



- Fixed scale $\mu = \mu_F = \mu_R = 80$ GeV
- CT10nlo, $\alpha_s(M_Z)|_{\text{CT10nlo}}$
- $M_t = 173.5$ GeV, on–shell

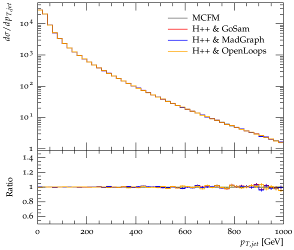
ttbar@NLO

[J. Bellm, S. Gieseke, D. Rauch, CR, S. Plätzer, P. Richardson, A. Wilcock; in prep.]

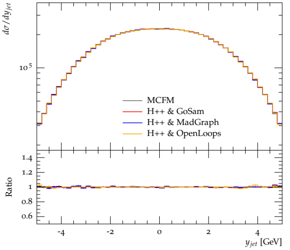
14TeV

Plots by D. Rauch

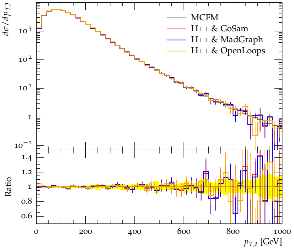
Jet Transverse Momentum $p_{T,jet}$



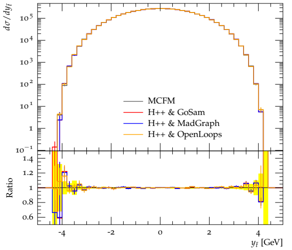
Jet Rapidity y_{jet}



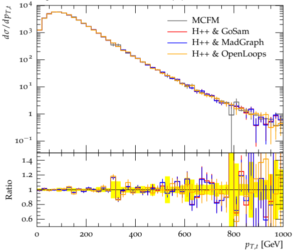
Antitop Quark Transverse Momentum $p_{T,\bar{t}}$



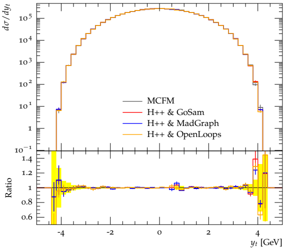
Antitop Quark Rapidity $y_{\bar{t}}$



Top Quark Transverse Momentum $p_{T,t}$

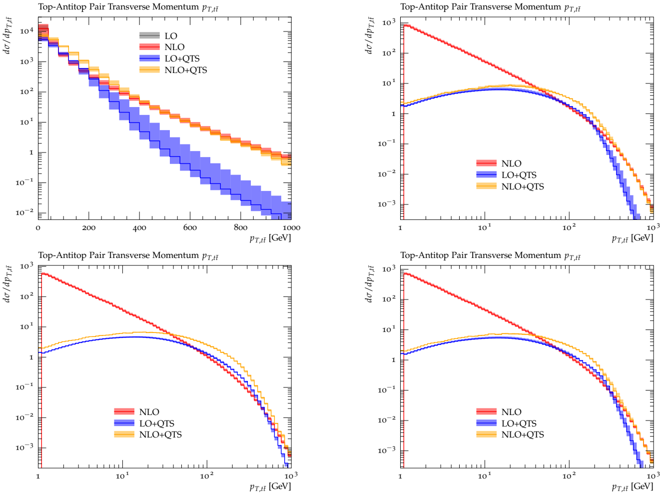


Top Quark Rapidity y_t



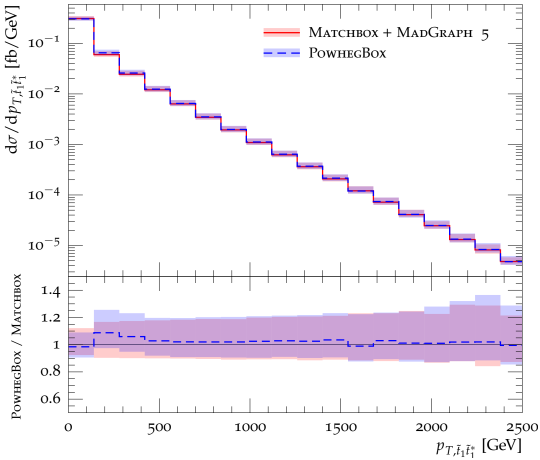
14TeV, NLO matched

Plots by D. Rauch



- MC@NLO–like matching to the angular ordered $\tilde{q}$–shower. Shower start scale $Q^2 = \mu^2$.
- Hard scale variation: $\mu^2 = \mu_F^2 = \mu_R^2$ by factors of 0.5 and 2
- Top: TopMinMTScale $\mu^2 = \mu^2_{\min_{t\bar{t}}\{m_T\}} = \min_{i=t,\bar{t}}\left(m_i^2 + p_{T,i}^2\right)$
- Bottom: TopMassScale $\mu^2 = \mu^2_{m_{t\bar{t}}} = (p_t + p_{\bar{t}})^2$, TopMTScale $\mu^2 = \mu^2_{m_{T,t\bar{t}}} = \sum_{i=t,\bar{t}}\left(m_i^2 + p_{T,i}^2\right)$

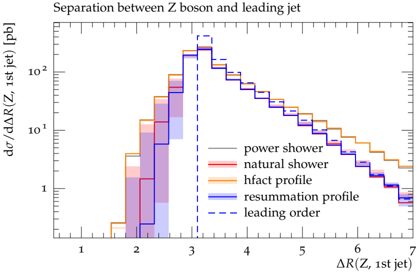
Plots by A. Wilcock

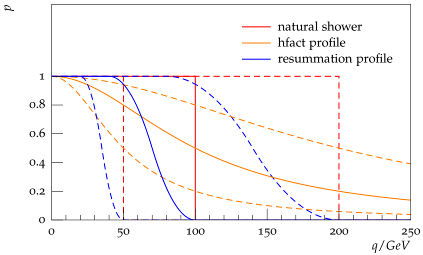


- Also $\tilde{b}$ production in progress (gluino contributions under control by subtracting resonant contributions).

Profile scales [S. Plätzer; unpublished]

Plots by S. Plätzer

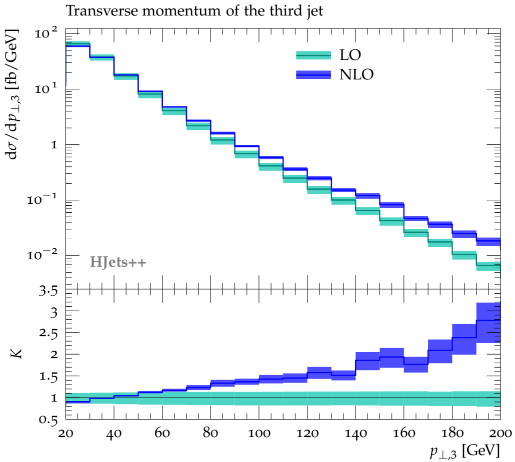




- Look at $\Delta R(Z, 1\text{st jet})$ in Z+jets
- LO hard process: Z inclusive
- Below π: Only large angle emission from the shower
- The POWHEG *hfact* profile shows the same behaviour as the "power shower"

- The *hfact* profile does not vanish at large scales
- The *resummation* profile vanishes for large scales within the boundaries of the hard cut–off of the "natural shower"
- In the Sudakov region: "natrual shower" and *resummation* profile strictly 1

8TeV

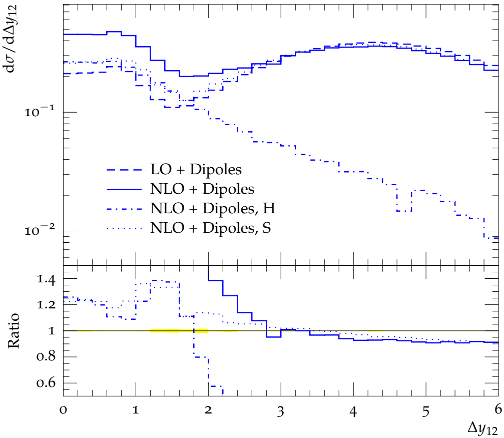


- HJETS++: MATCHBOX-plugin for electroweak $H+2,3,4$j at LO, $H+2,3$j NLO, including all Higgs-Strahlung, VBF and interference contributions.
- $H+3$jets in VBF with HJETS++
- At NLO a new channel opens up
- Scale uncertainty reduces further with stricter VBF cuts

$H + 2$jets NLO matched [F. Campanario, T. Figy, M. Sjödahl, S. Plätzer; unpublished]

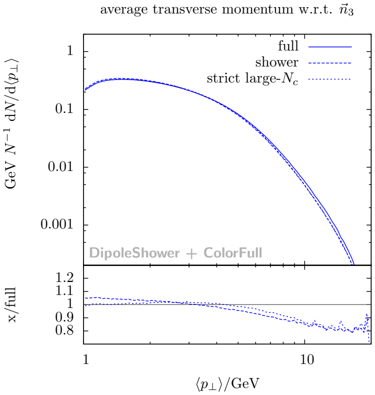
8TeV

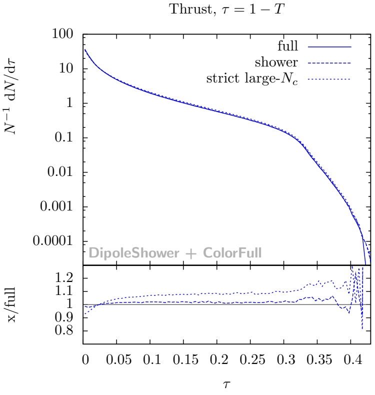
Plots by S. Plätzer



- Jet separation between $1st$ and $2nd$ jet
- Close to VBF cuts (large separation): Small corrections
- Appart from VBF cuts (small separation): Larger corrections

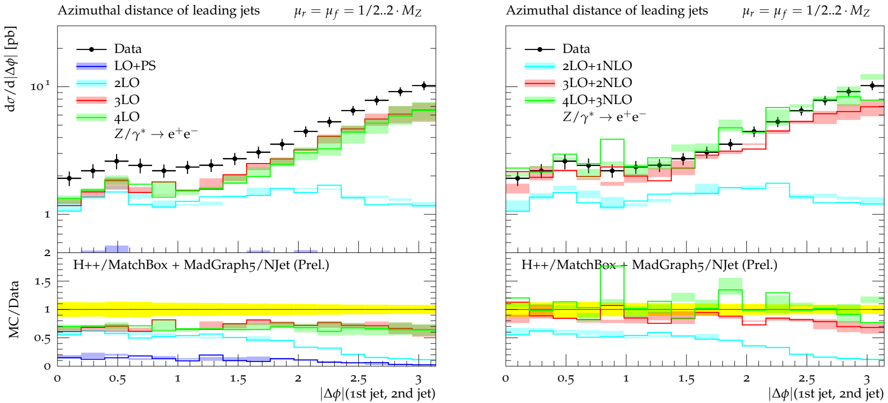
- Color matrix element corrections
- Splitting kernels with full color information





- >3 jets events. Thrust axis from 3 hardest jets (e.g. 2 recoiling vs. 3rd)
- Average $p_\perp$ of all others, not lying in that plane
- Top: Full subleading–N_c improved
- Middle: C_F exact
- Bottom: Strict large–N_c limit, $C_F = \frac{C_A}{2}$

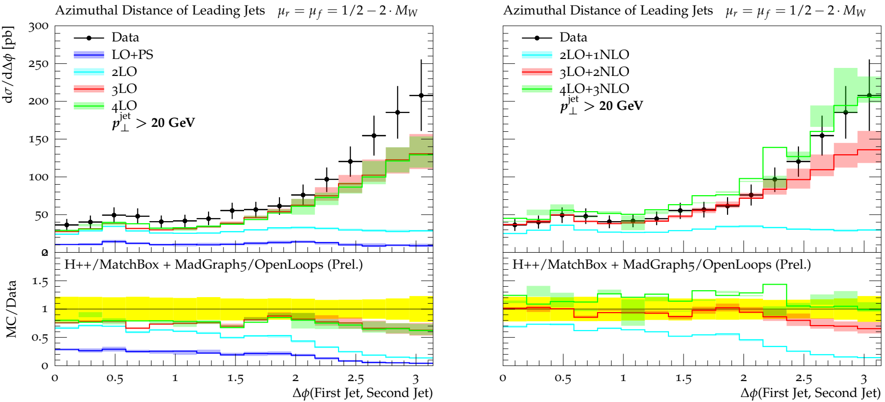
Plots by J. Bellm



- ATLAS_2013_I1230812_EL
- Azimuthal distance of the two leading jets
- Only described correctly by adding 3NLO = V@NLO + V1j@NLO + $V2j$@NLO

W+jets (NLO merged) [J. Bellm, S. Gieseke, S. Plätzer; in prep.]

Plots by J. Bellm



- Atlas_2012_I1083318
- Azimuthal distance of the two leading jets
- Only described correctly by adding 3NLO = V@NLO + $V1$j@NLO + $V2j$@NLO

- With the advent of the BLHA2 standard to interface Monte Carlo event generators and one–loop matrix element providers, the HERWIG++ event generator has expanded its range of applicability to a multitude of underlying hard processes at NLO QCD.
- The new NLO development is centered on the MATCHBOX framework, which turns fixed NLO QCD calculations into parton shower matched calculations – to be matched to the two parton shower variants of HERWIG++.
- Discussed briefly the functionality of the MATCHBOX framework and also how to setup a computation in the new framework.
- Discussed a few selected results, obtained within the new framework and in associated projects.
- The whole framework has been extensively tested and is well on its way.
- More studies are in prep. E.g. $t\bar{t}j$@NLO, heavy jets in 4 vs. 5FS [S. Plätzer, CR]
  or WW production in ggF [GOSAM & J. Bellm, S. Gieseke, S. Plätzer, CR]
  also an interfacing to RECOLA [RECOLA & S. Plätzer, CR]
- Final adjustments are being made and a release is nearing completion.

Image tune: J. Bellm

THANK YOU FOR YOUR ATTENTION

And stay tuned on https://herwig.hepforge.org/

- Herwig++ and related

  [Bähr et al., Herwig++ Physics and Manual; Eur.Phys.J. C58 (2008) 639-707; arXiv:0803.0883]

  [Bellm et al., Herwig++ 2.7 Release Note; arXiv:1310.6877]

  [Plätzer, Gieseke; Dipole Showers and Automated NLO Matching in Herwig++; Eur.Phys.J. C72 (2012) 2187; arXiv:1109.6256]

  [Plätzer, Gieseke; Coherent Parton Showers with Local Recoils; JHEP 1101 (2011) 024; arXiv:0909.5593]

- NLO QCD subtraction
  - Dipole subtraction [Catani, Seymour '96; Phaf, Weinzierl '01; Catani, Dittmaier, Seymour, Trocsanyi '02; Dittmaier, Kasprzik '08; Papadopoulos, Worek '09; Goetz, Schwan, Weinzierl '12]
  - Antenna subtraction [Kosower '97; Gehrmann-de Ridder, Gehrmann, Glover '05; Daleo, Gehrmann, Maitre '06; Gehrmann-de Ridder, Ritzmann '09]
  - Residue subtraction [Frixione, Kunszt, Signer '95; Del Duca, Somogyi Trocsanyi '05; Frixione '11]
  - Nagy–Soper subtraction [Nagy, Soper '07; Chung, Kramer, Robens '10; Bevilacqua, Czakon, Kubocz, Worek '13]
  - Many automated implementations exist:

    [Weinzierl '05; Gleisberg, Krauss '07; Seymour, Tevlin '08; Hasegawa, Moch, Uwer '08; Frederix, Gehrmann, Greiner '08; Czakon, Papadopoulos, Worek '09; Plätzer, Gieseke '12]

- One–loop programs
  - BlackHat [Bern, Dixon, Febres-Cordero, Ita, Kosower, LoPresti, Maitre, Ozeren, Höche]
  - NJet [Badger, Biedermann, Uwer, Yundin]
  - OpenLoops [Cascioli, Lindert, Maierhoefer, Pozzorini]
  - GoSam [Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, v. Soden-Fraunhofen, Tramontano]
  - MG5_aMC@NLO [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro]
  - NLOX [Reina, Schutzmeier]
  - Recola [Actis, Denner, Hofer, Scharf, Uccirati]
  - MCFM [Campbell, Ellis, Giele, Williams]
  - VBFNLO [Baglio, Bellm, Campanario, Feigl, Frank, Figy, Kerner, Ninh, Palmer, Rauch, Roth, Schissler, Schlimpert, Zeppenfeld]

- More tensor reduction programs:

  Golem95 [Binoth, Cullen, Greiner, Guffanti, Guillet, Heinrich, Karg, Kauer, Reiter, Reuter]

  MadGolem [Binoth, Goncalves Netto, Lopez-Val, Mawatari, Plehn, Wigmore]

  PJFry [Fleischer, Riemann, Yundin]

- More programs based on cut techniques:

  HelacNLO [Bevilacqua, Czakon, Garzelli, vanHameren, Kardos, Papadopoulos, Pittau, Worek]

  MadLoop [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]

  Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi]

- Matching/Merging
  - [Bengtsson, Sjöstrand '87; Gustafson, Pettersson '88; Seymour '95; Lönnblad '96; Miu, Sjöstrand '99]
  - [Nason '04; Aliolo, Nason, Oleari, Re '08]
  - [Frixione, Webber, '02; Frixione, Webber, '06]
  - [Catani, Krauss, Kuhn, Webber '01; Lönnblad '01; Höche, Krauss, Schumann, Siegert '09; Hamilton, Richardson, Tully '09]
  - [Caravaglios, Mangano, Moretti, Pittau '99; Mangano, Moretti, Pittau '02; Mangano, Moretti, Piccinini, Pittau '03; Alwall et al. '08]
  - [Mrenna, Richardson '04]
  - [Krauss '02; Lavesson, Lönnblad '05]
  - [Lavesson, Lönnblad '08; Hamilton, Nason '10]
  - [Giele, Kosower, Skands '08]
  - [Frixione, Nason, Oleari; Frederix, Frixione]
  - [Plätzer '12; Prestel, Lönnblad '12; Höche, Krauss, Schönherr, Siegert '12]