Higgs at NLO with Herwig++

Simon Plätzer

– On behalf of the Herwig++ team –

Institute for Particle Physics Phenomenology, Durham University

and

School of Physics and Astronomy, University of Manchester

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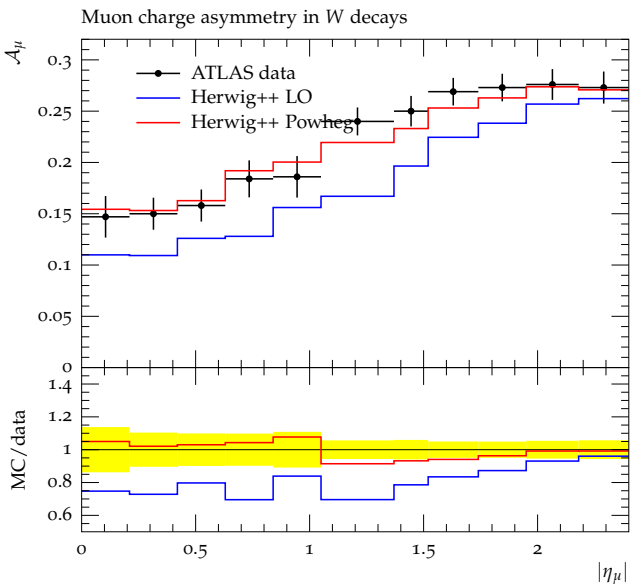
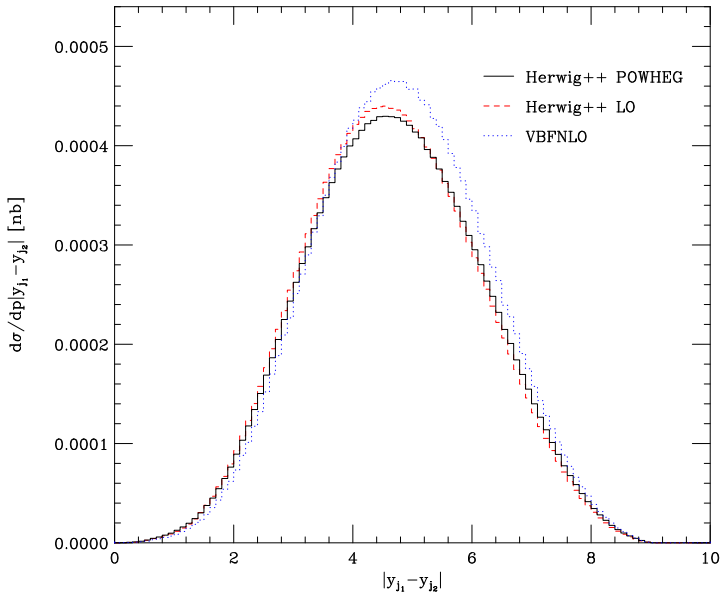
Current status and motivation.

Dedicated approaches to NLO matching, largely hand-made or semi-automated.
Many processes available in current release: DY, $gg \to h$, VBF, VH, VV, h decays.



$pp \to W$

[K. Hamilton et al. – JHEP 0904 (2009) 116]



VBF Higgs production

[L. D'Errico, P. Richardson – EPJ C72 (2012) 2042]

Change in paradigm: Need for an automated, fully integrated framework.

$\to$ Uncertainties and merging require full control of fixed-order input.

Outline.

- (N)LO Matrix Elements for Herwig++ with Matchbox
- Matching Validation & Systematics
- Shower & Matching Uncertainties
- Outlook: BSM, (N)LO merging
- Summary

Matchbox Overview.

$$\sigma_{\text{NLO}} = \int_n \mathrm{d}\sigma_{\text{LO}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}_{n,0}|^2 \end{pmatrix} + \int_n \left[\mathrm{d}\sigma_{\text{V}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle, |\mathcal{M}_{n,1}\rangle \\ 2\text{Re}(\langle \mathcal{M}_{n,0} | \mathcal{M}_{n,1} \rangle) \end{pmatrix} + \int_1 \mathrm{d}\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$
$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} - \mathrm{d}\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$
$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\text{R}} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - \mathrm{d}\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} \right]$$

Interfaces at amplitude level

- Color bases provided, including interface to `ColorFull`.
  [M. Sjödahl, SP]
- Spinor helicity library and caching facilities.
- MadGraph5.
  [MadGraph & J. Bellm, S. Gieseke, SP, A. Wilcock]
- Some in-house calculations and parts of `HJets++`.
  [F. Campanario, T. Figy, SP, M. Sjödahl]

Interfaces at squared amplitude level

- Dedicated interfaces.
  [HEJ & SP]
  [nlojet++ & J. Kotanski, J. Katzy, SP]
- BLHA2.
  [GoSam & J. Bellm, S. Gieseke, SP, C. Reuschle]
  [NJet & SP]
  [OpenLoops & J. Bellm, S. Gieseke]
  [VBFNLO & K. Arnold, S. Gieseke, SP]

Matchbox infrastructure

based on [SP & S. Gieseke – Eur.Phys.J. C72 (2012) 2187]

- Process generation and bookkeeping, integration.
- Automated Catani-Seymour dipole subtraction.
- Diagram-based mutli-channel phase space.

Shower plugins

matching details & uncertainties [in preparation]

- Dipole shower $D(p_\perp)$.
- Angular ordered shower $P(\tilde{q})$.
- ME correction $R_{\text{ME}}(p_\perp)$, including adaptive sampling.

Matchbox Overview.

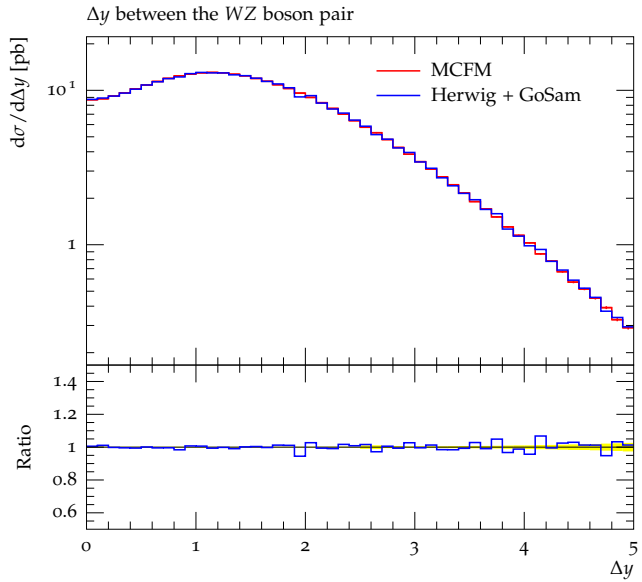
Steering as 'plain' Herwig++ – no codes to run separately, no event files.

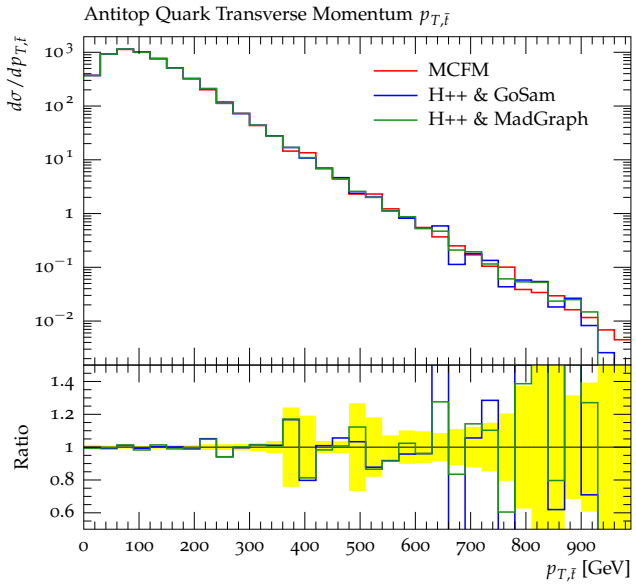
```
insert LHCEventHandler:SubProcessHandlers[0] PPFactory

# choose process; couplings wrt LO, QCD NLO added by default
set PPFactory:OrderInAlphaS 1
set PPFactory:OrderInAlphaEW 2
do PPFactory:Process p p e+ e- j

# choose amplitude providers
set GenericProcesses:TreeLevelAmplitude MadGraph
set GenericProcesses:OneLoopAmplitude OpenLoops

# enable matching to angular ordered shower
set PPFactory:ShowerApproximation QTildeMatching

# assess perturbative uncertainties
set PPFactory:FactorizationScaleFactor 0.5
set ShowerHandler:HardScaleFactor 2.0
```

`./Herwig++ read LHC-Matchbox.in & ./Herwig++ run LHC-Matchbox.run`
does all the job (plus: extensive **support for parallelization**).

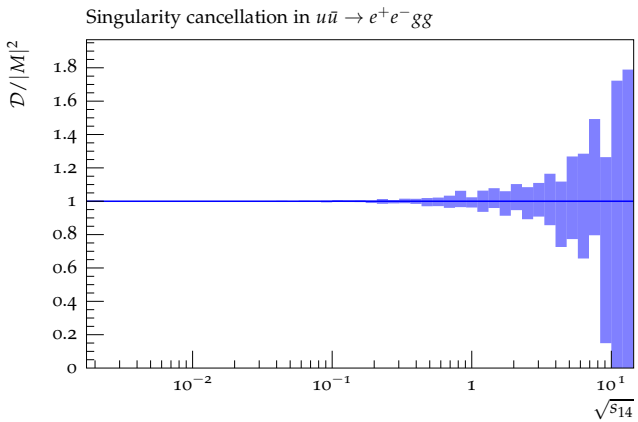
Matchbox Validation.

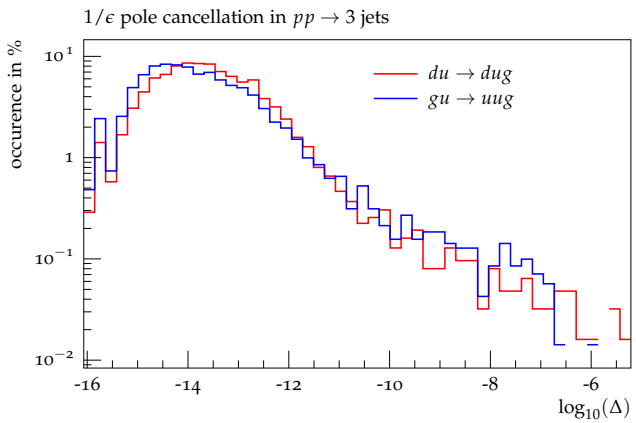
Extensive validation against e.g. MCFM [N. Fischer, D. Rauch, C. Reuschle]





Various internal cross checks: Subtraction checks, pole cancellation.





$pp \to Z +$ jet (GoSam)

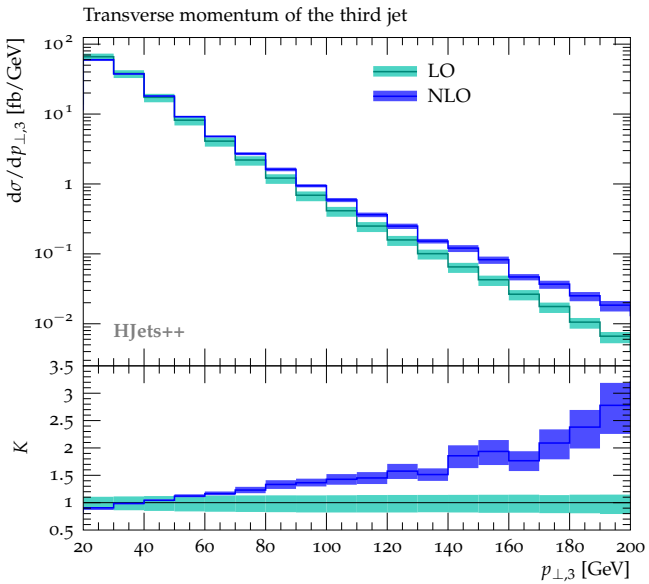
$pp \to 3$ jets (NJet)

NLO Calculations with Matchbox.

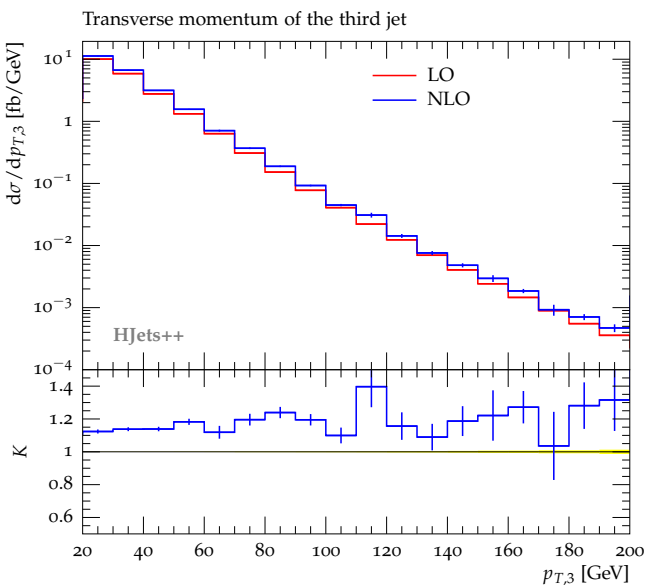
Electroweak H+Jets production with `HJets++`

[F. Campanario, T. Figy, SP, M. Sjödahl – PRL 111 (2013) 211802]

- Employs all of Matchbox's infrastructure for a hadron collider $2 \to 4$ process.
- Hybrid interfaces of amplitude and squared amplitude infrastructure, internal cross checks possible.



Inclusive cuts.



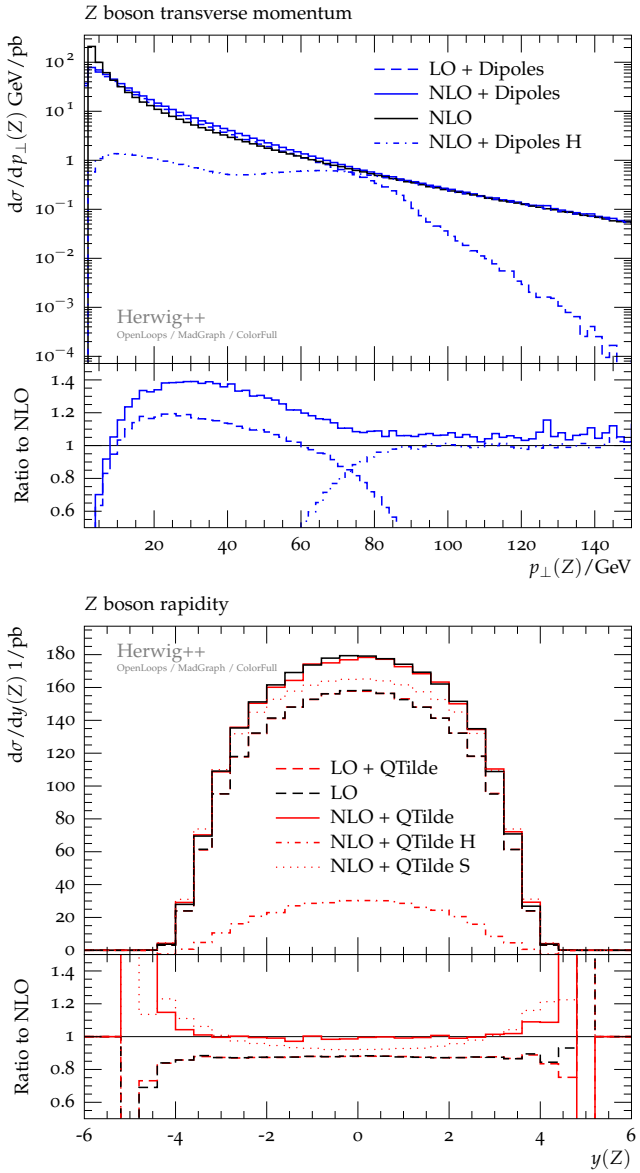
VBF cuts.

$pp \to H + 3$ jets @ 14 TeV – inlcudes all VBF and Higgs-strahlung contributions
Have $pp \to H + 2$ jets available as well.

[validated against Ciccolini, Denner, Dittmaier – Phys.Rev.Lett. 99 (2007) 161803]

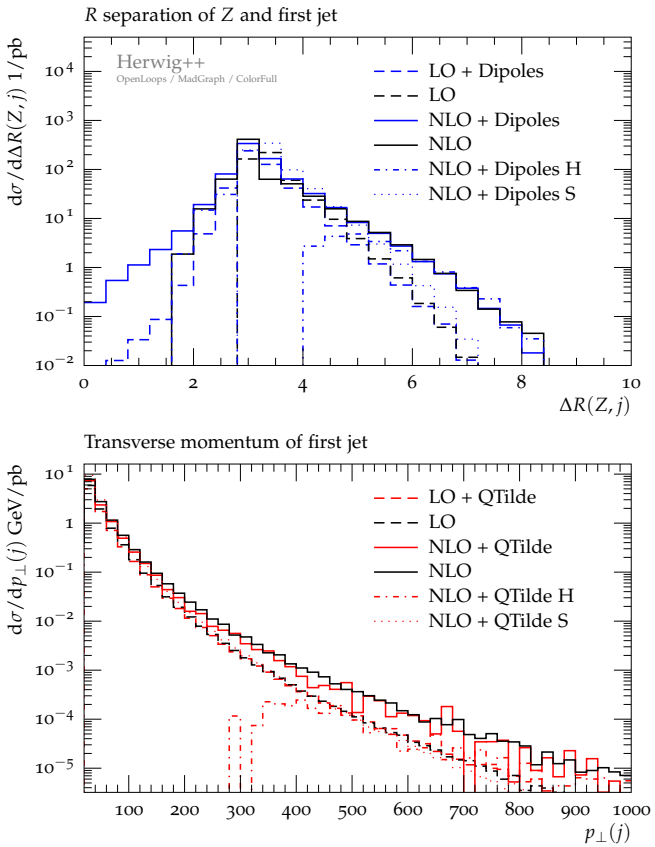
Matching Validation & Systematics.

Compare fixed order, unshowered S and H events, and full simulation.



Prime validation: inclusive Z.

Non-trivial application: Z plus jet

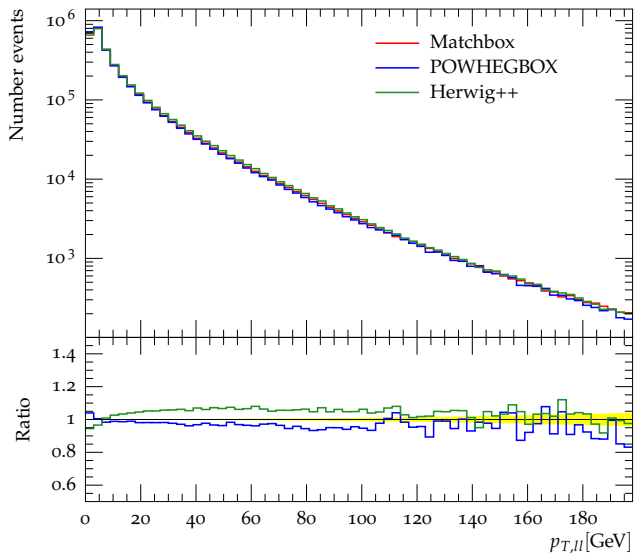


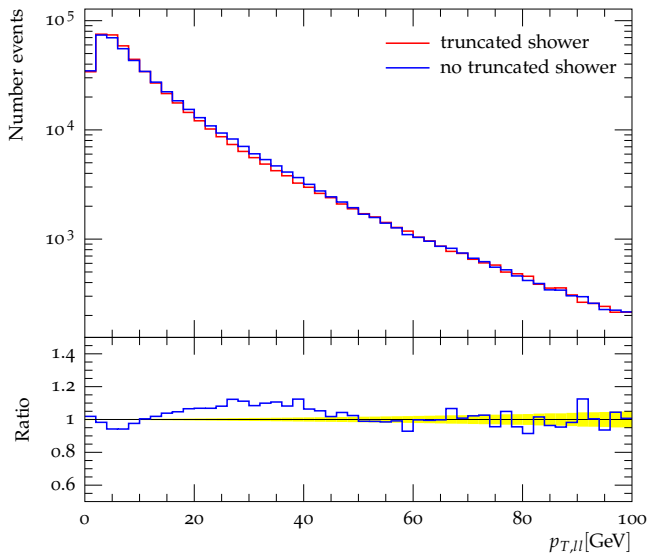
Matching Validation & Systematics: Powheg-type.

[A. Wilcock, P. Richardson, SP – work in progress]

Powheg-type matching smoothly integrated into Matchbox

- Adaptive sampling of ME correction Sudakov [SP – Eur.Phys.J. C72 (2012) 1929]
- Various profile scale choices and uncertainty estimates
- Can check impact of truncated showering





Shower & Matching Uncertainties.

Shower uncertainties until now poorly understood.

- Various scales in the game: μ_R, μ_F, μ_Q.
- Role of μ_Q not a priory clear (no variable hard scale for a.o. showers, only $p_\perp$ veto)
- μ_R, μ_F in hard process vs. in the shower?

Matching is a way more complicated setting!

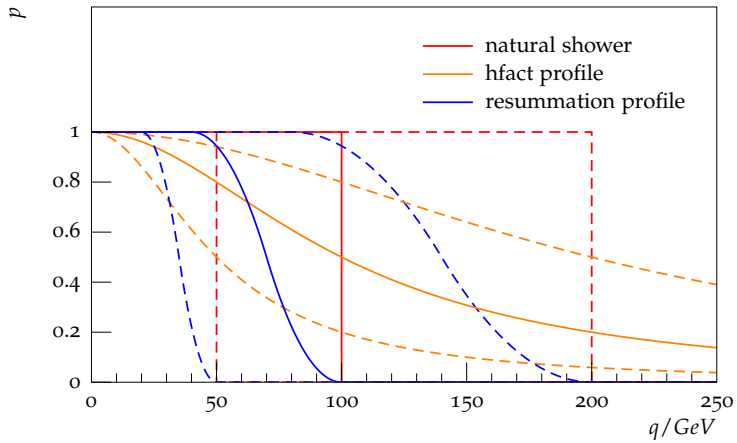
- Some expectations confirmed in matched setups.
- Surprises in uncertainties for higher jet multiplicities.
- Need to profile hard emission to avoid NNLO jumps.

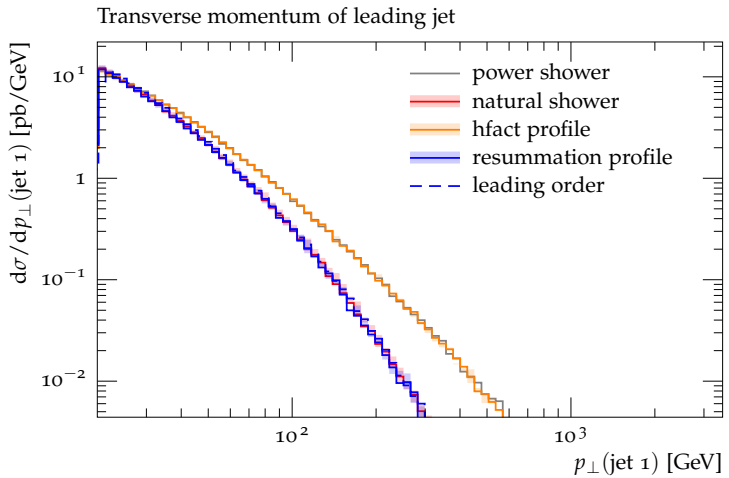
Upshot: Cross-benchmark between different showers with and without matching.

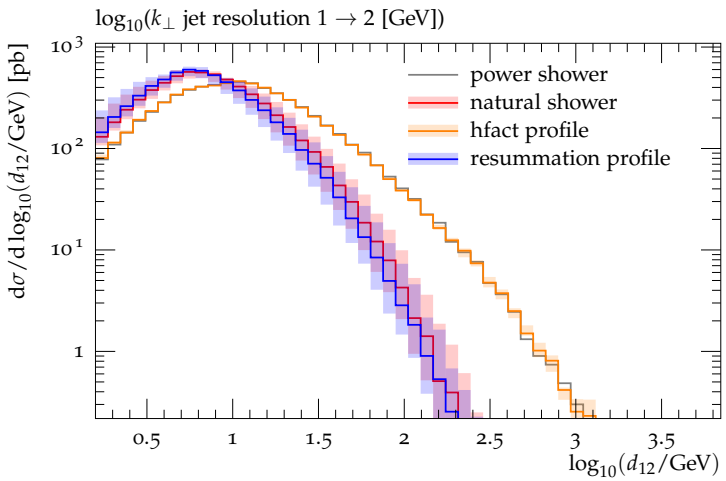
Hopefully more insight soon – needs close connection with resummation community.

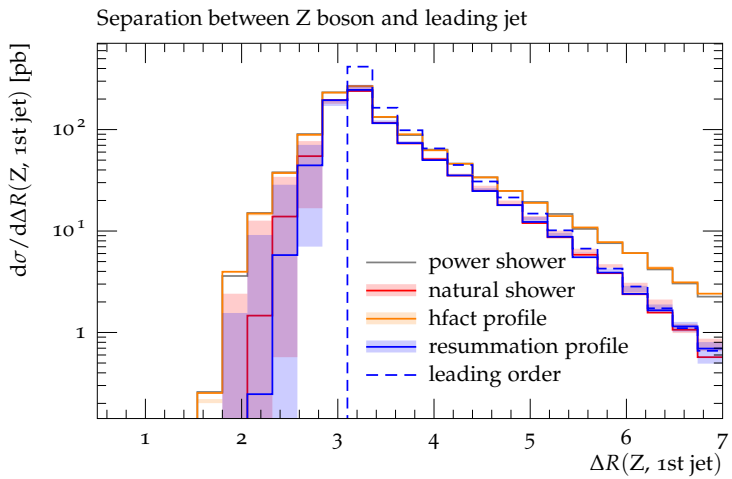
μ_Q variations and profile scales.

Important to validate uncertainties at **leading order**:
Matching may hide important details. Do we see what we expect?



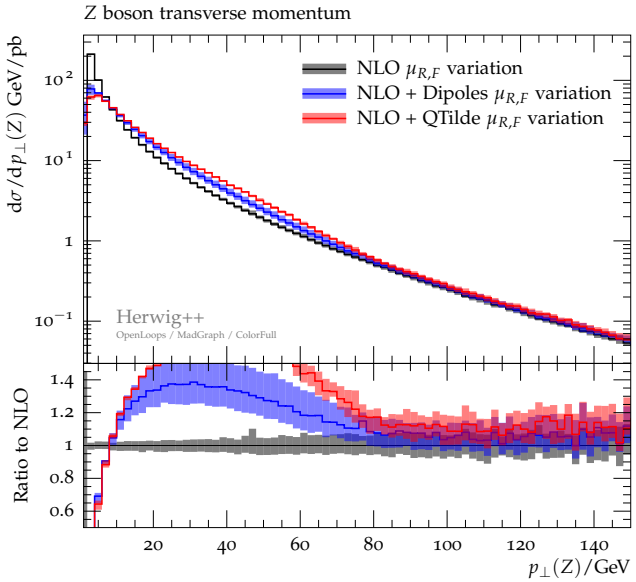


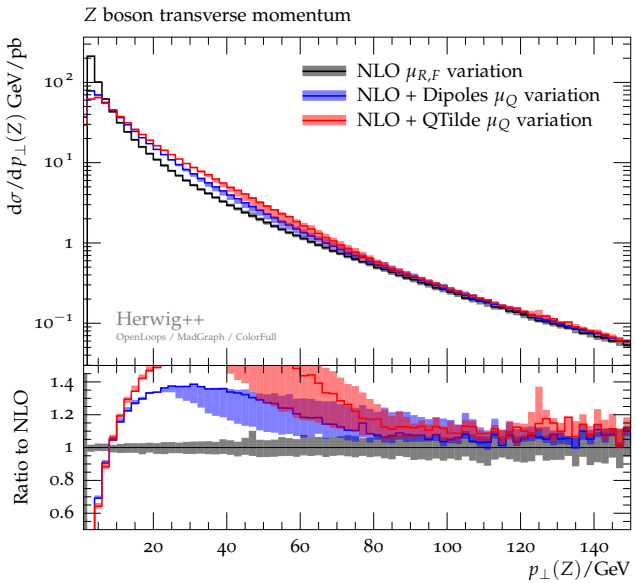




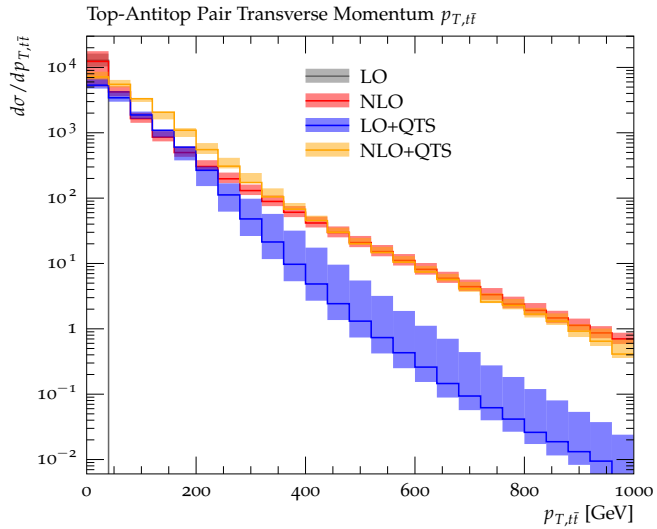
Full benchmark of uncertainties in progress – S. Gieseke & SP

Matching uncertainties.

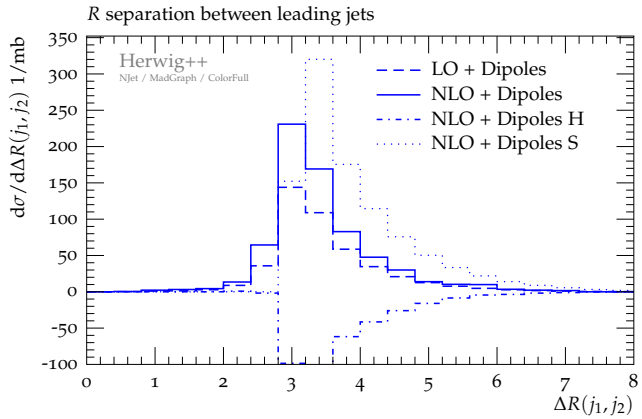




$t\bar{t}$ at NLO [D. Rauch, C. Reuschle]

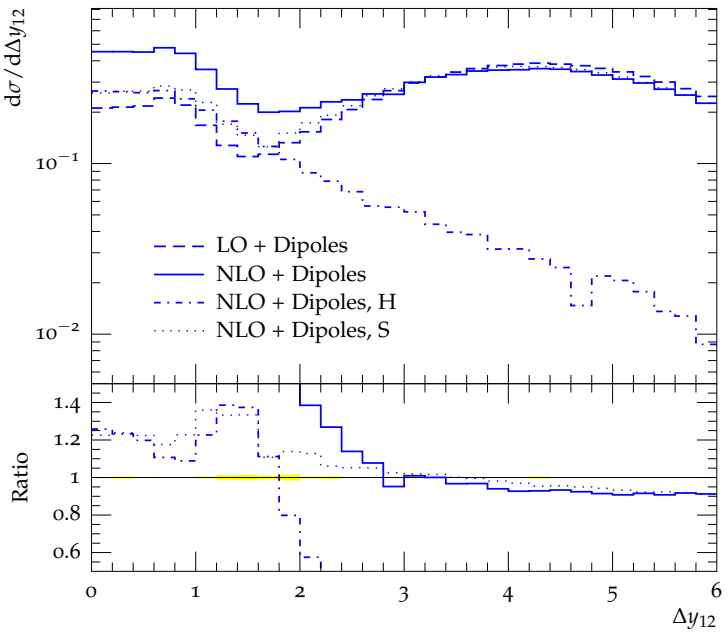


More (jetty) processes in progress, e.g. dijets:



Matchbox: Higgs specific.

EW $h + 2j$: DipoleShower MC@NLO
Herwig++/HJets++ – Inclusive cuts.



[F. Campanario, SP, M. Sjödahl – work in progress]

A number of processes accessible:

- Builtin $gg \to h$, $b\bar{b} \to h$
- VH from OpenLoops & MadGraph
- QCD Higgs plus Jets from GoSam & MadGraph
- EW Higgs plus Jets from `HJets++`
- Various from VBFNLO
- ... whatever externals can do.

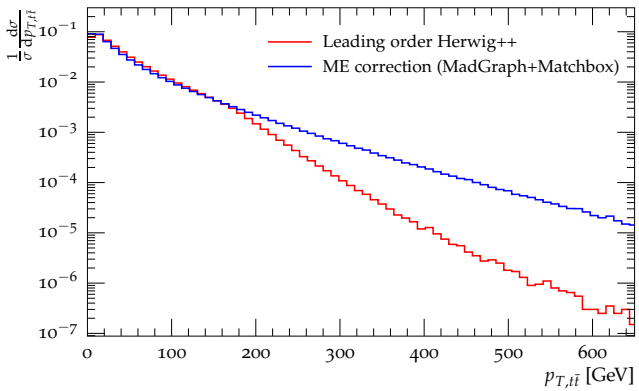
Outlook: BSM with Matchbox.

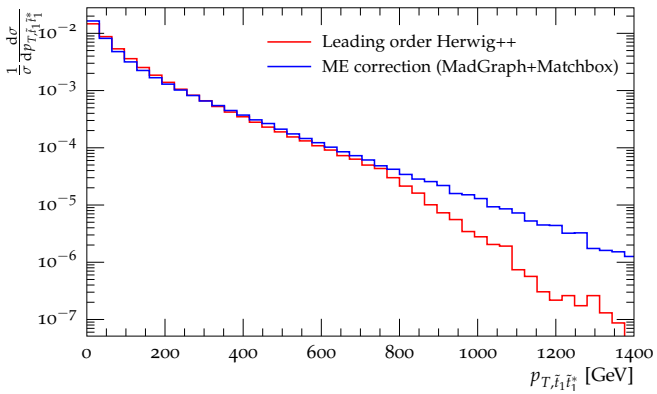
[A. Wilcock, P. Richardson, SP – work in progress]

Study impact of matrix element corrections in $t\bar{t}$ and $\tilde{q}\tilde{q}$ production.

- First step to full NLO matching.
- Impact on exclusion bounds.
- Matching condition $\leftrightarrow$ 'diagram subtraction'.

$t\bar{t}$ and $\tilde{t}\tilde{t}$ production at 14 TeV.



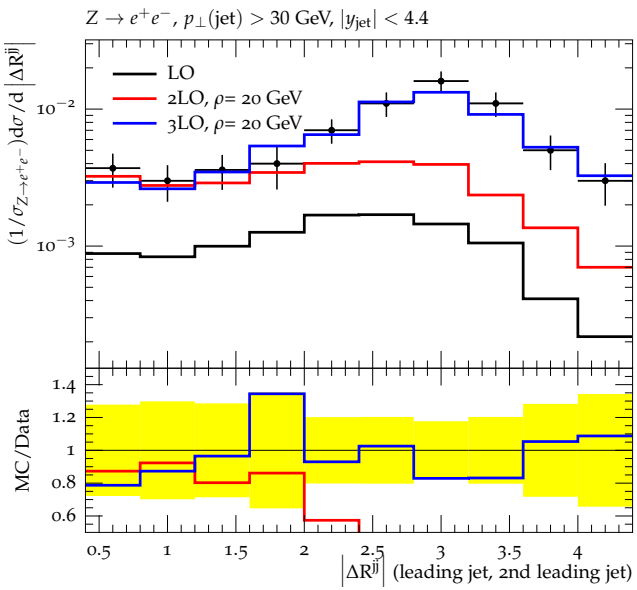


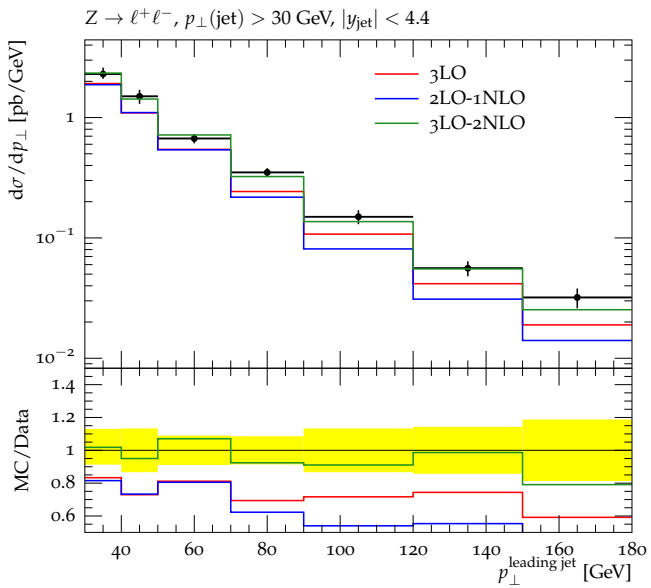
Outlook: (N)LO Merging.

[J. Bellm, S. Gieseke, SP – work in progress]

Matchbox framework provides unique possibilities for exploring new merging algorithms.

Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel –JHEP 1303 (2013) 166]





Z plus jets from ATLAS: LO and NLO merging.

Summary.

Current release: Dedicated approaches to NLO matching.
Various **Higgs processes** and backgrounds available: $gg \to h$, VBF, VH, VV.
Including NLO matched Higgs to $Q\bar{Q}$ decays.
hh available at LO with full mass dependence. [A. Papaefstathiou]

Herwig++ 3.0 faces change in paradigm:
Automated NLO $\times$ Two showers $\times$ Two matching algorithms.

- Matching and uncertainties under validation for a bunch of processes.
- Needs careful investigation for several process classes, especially with jets.

Related: BSM applications, NLO merging, first attempts on EW corrections.

Higgs specific:

- `HJets++` will be released along with Herwig++ 3.0
  $\to$ EW Higgs plus jets production at NLO QCD
- Large-m_t NLO fully supported using GoSam amplitudes
- Interfaces to MadGraph, OpenLoops, VBFNLO ...

Stay tuned on `herwig.hepforge.org`**.**