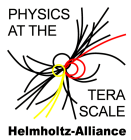
NLO Event Generation with Herwig++

Simon Plätzer

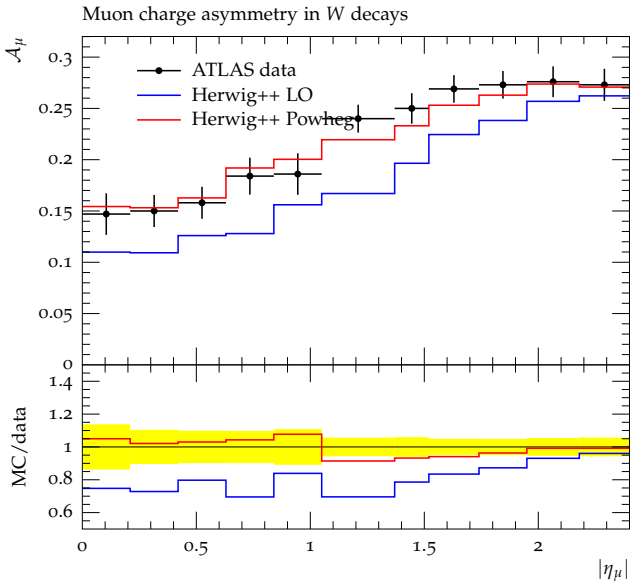
DESY

– on behalf of the Herwig++ collaboration –



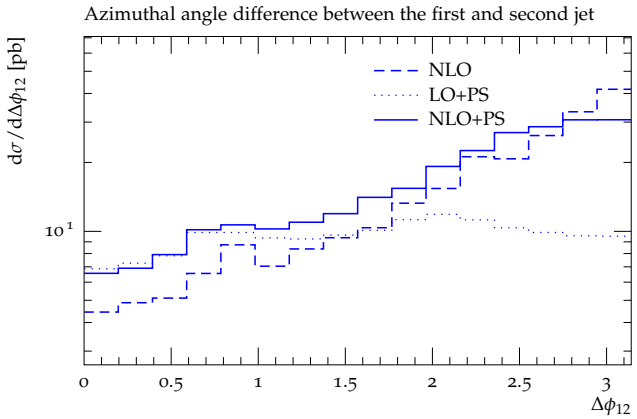
Overview.

Dedicated approaches to NLO matching, largely hand-made or semi-automated.
Many processes available in current release, well established.



$pp \to W$

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



Z+jet

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

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

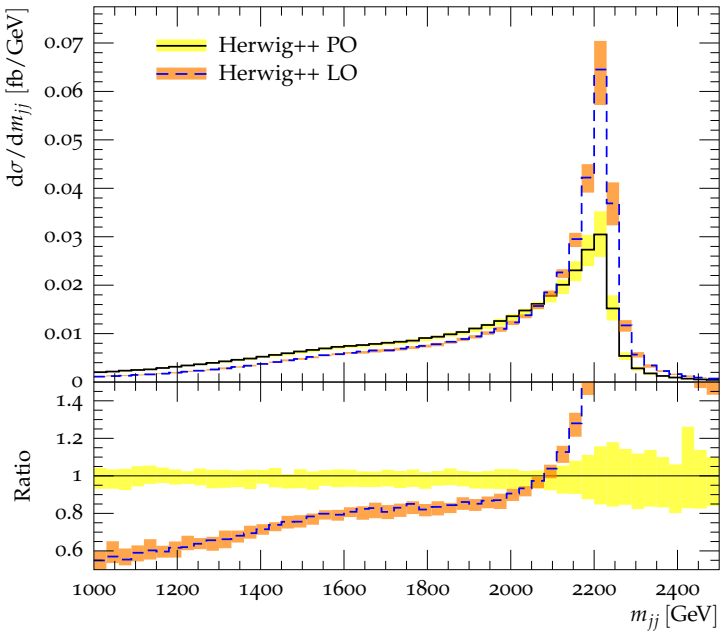
$\to$ Uncertainties and merging require full control of fixed-order input.

Dedicated NLO approaches: BSM Decay Chains.

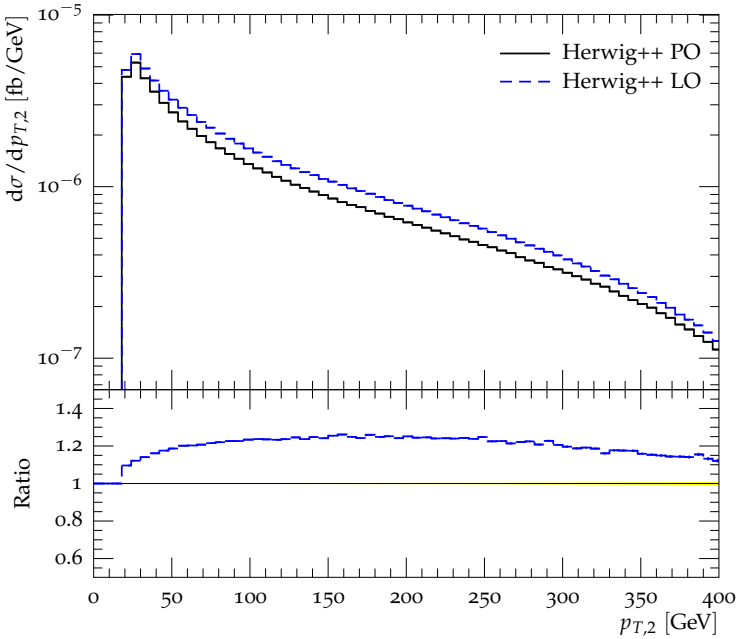
Powheg matching integrated with fexible and generic Herwig++ BSM infrastructure.

[P. Richardson, A. Wilcock – Eur.Phys.J. C74 (2014) 2713]

Jet pair mass in RS graviton decay.



$p_\perp$ distribution in CMSSM squark decay.



Outline.

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

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.

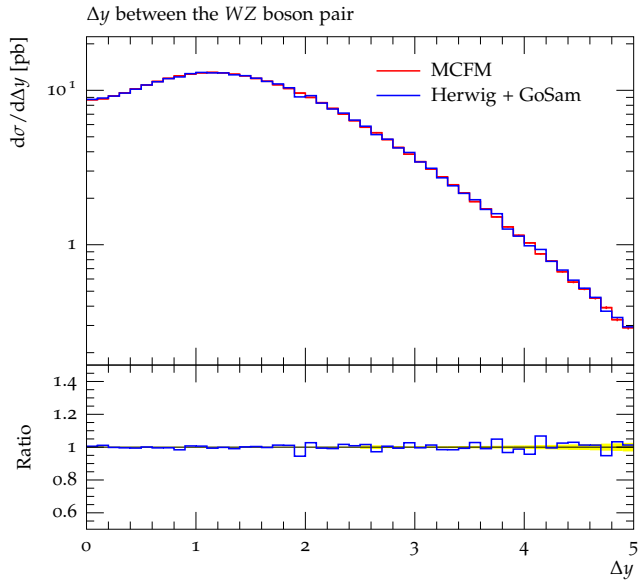
Shower plugins

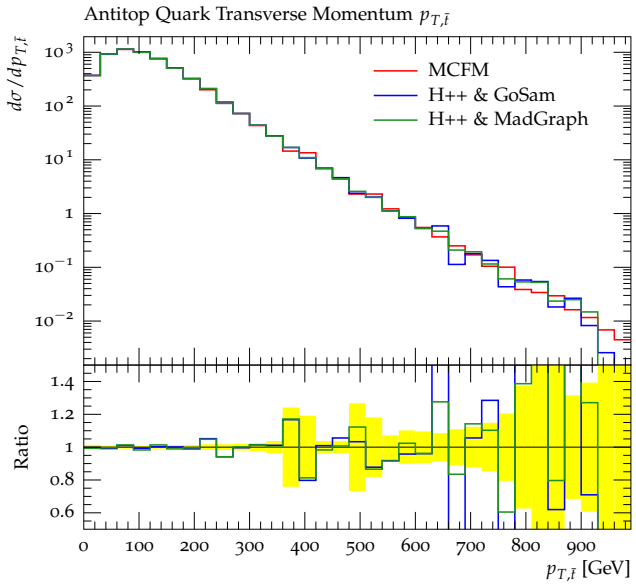
matching details & uncertainties [in preparation]

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

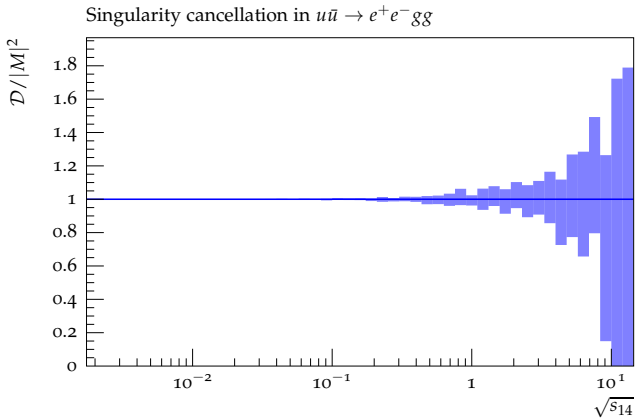
Matchbox Validation.

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

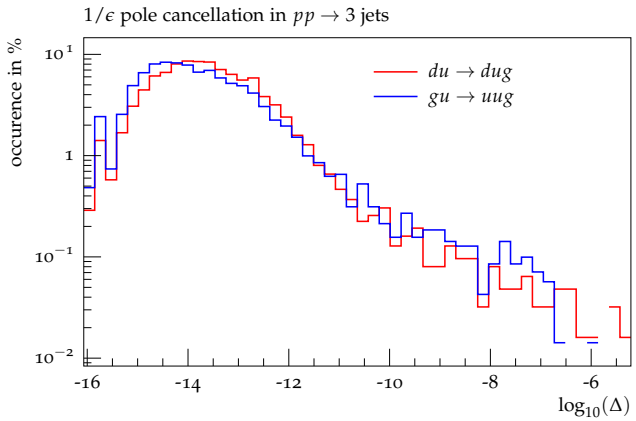




Various internal cross checks: Subtraction checks, pole cancellation.



$pp \to Z$ + jet (GoSam)



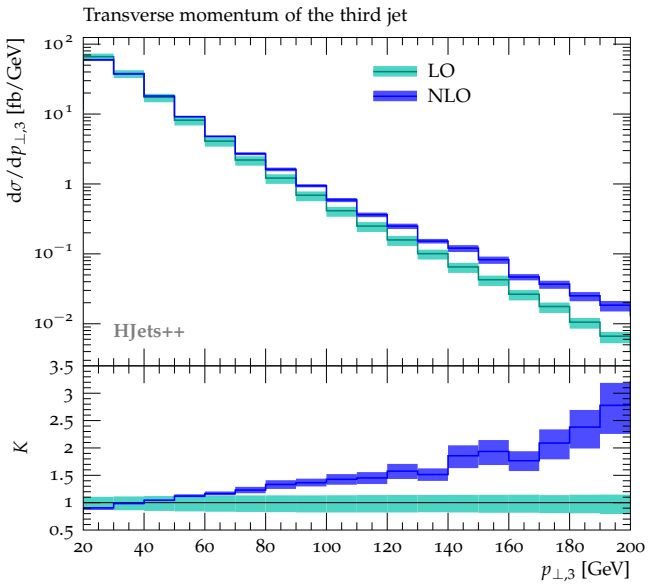
$pp \to 3$ jets (NJet)

NLO Calculations with Matchbox.

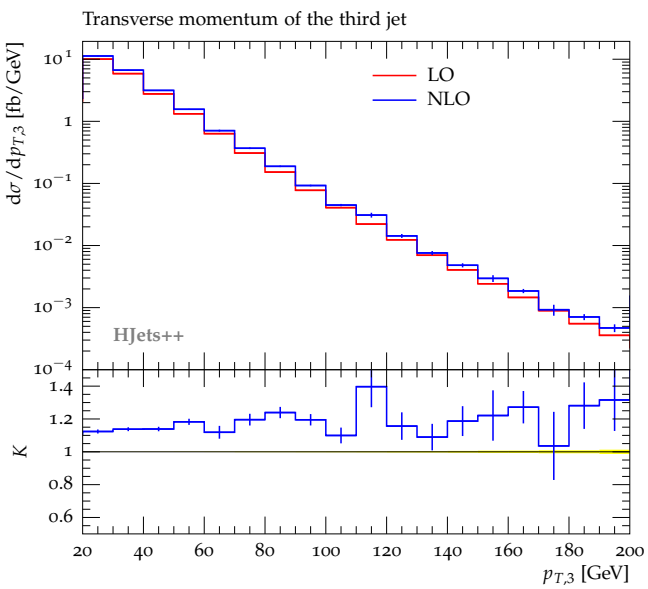
Electroweak H+Jets production with `HJets++`

[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.



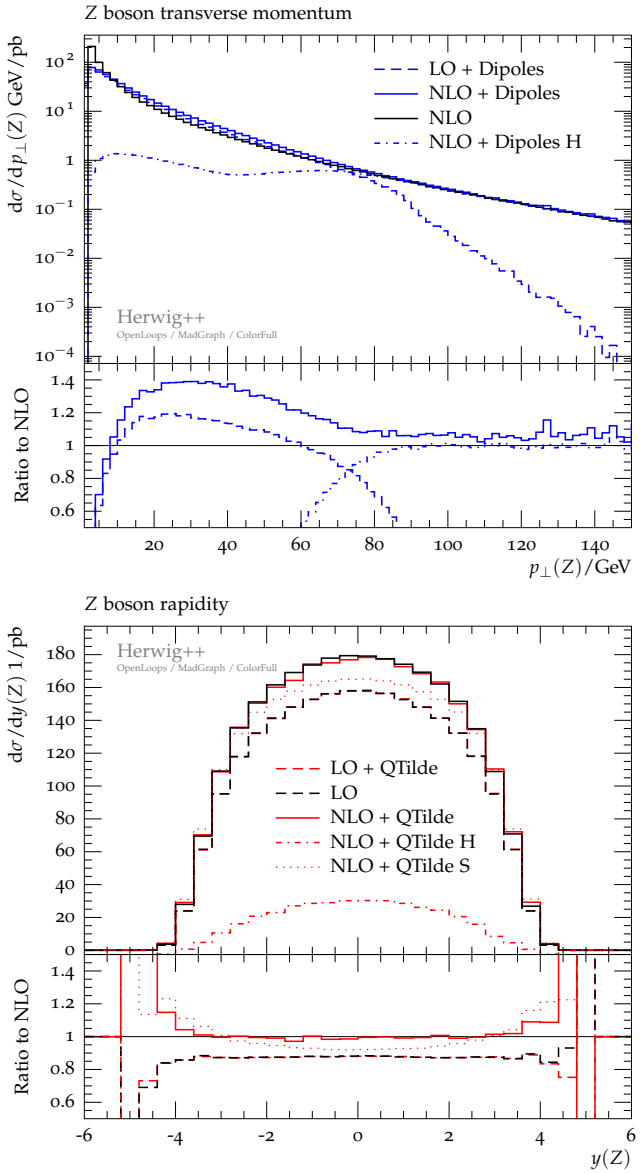
VBF cuts.

$pp \to H + 3$ 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]

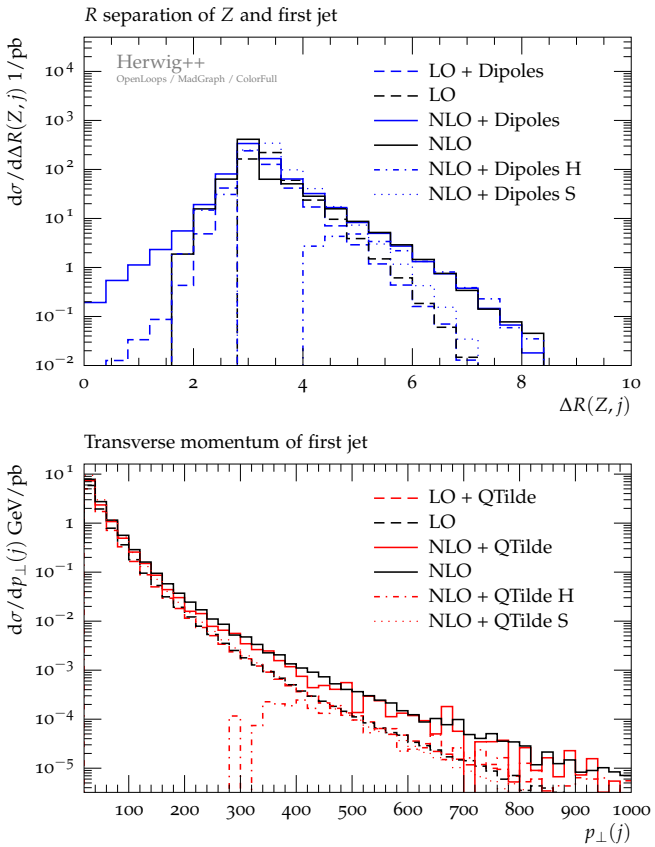
Matching Validation & Systematics.

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



Prime validation: inclusive Z.

Non-trivial application: Z plus jet

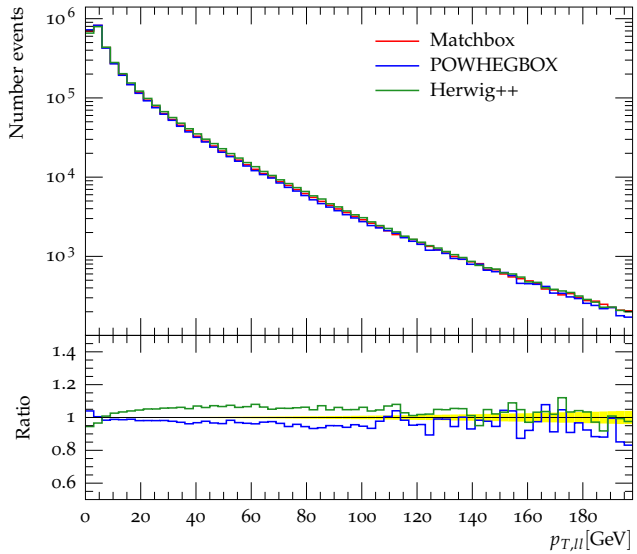


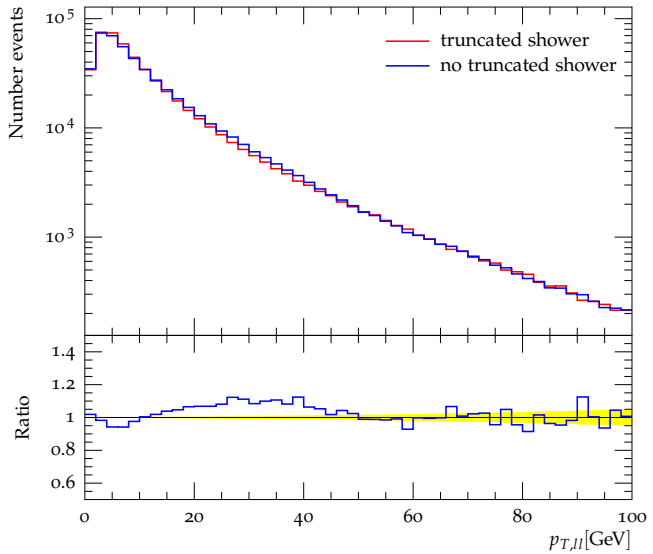
Matching Validation & Systematics: Powheg-type.

[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!

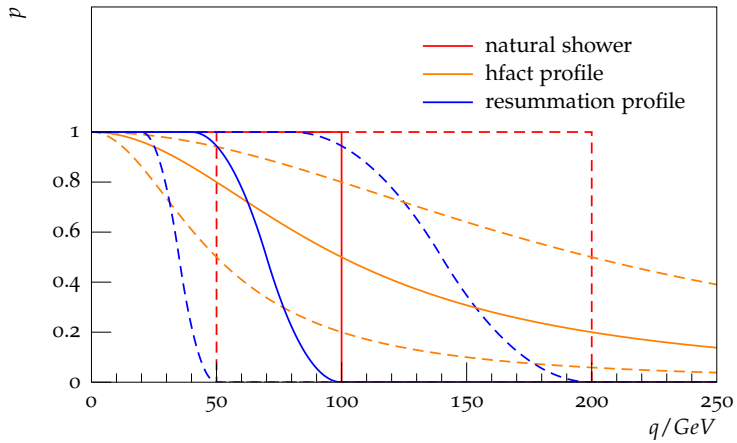
- Some expectations confirmed in matched setups.
- Surprises in uncertainties for higher jet multiplicities.
- Need to profile hard emission to avoid NNLO jumps.

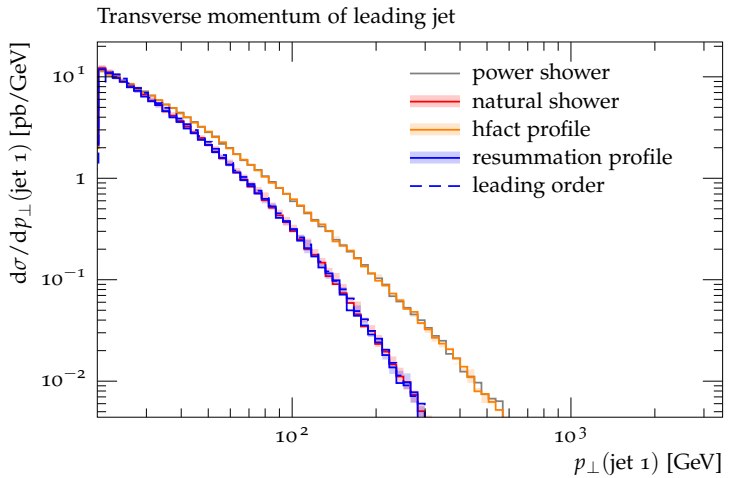
Upshot: Cross-benchmark between different showers with and without matching.

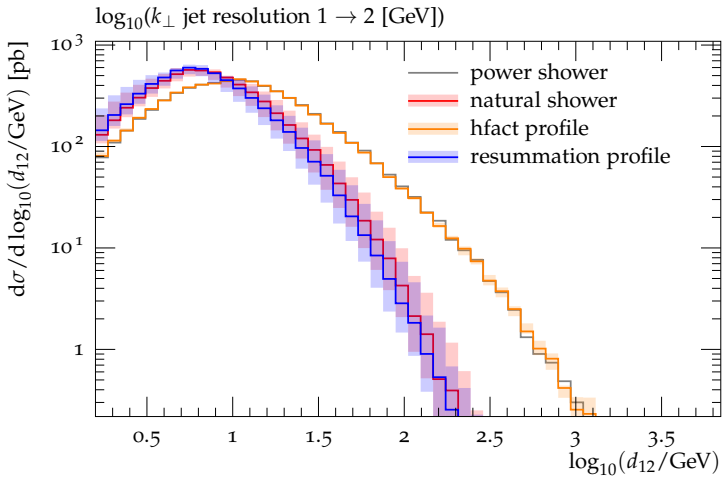
Hopefully more insight soon – needs close connection with resummation community.

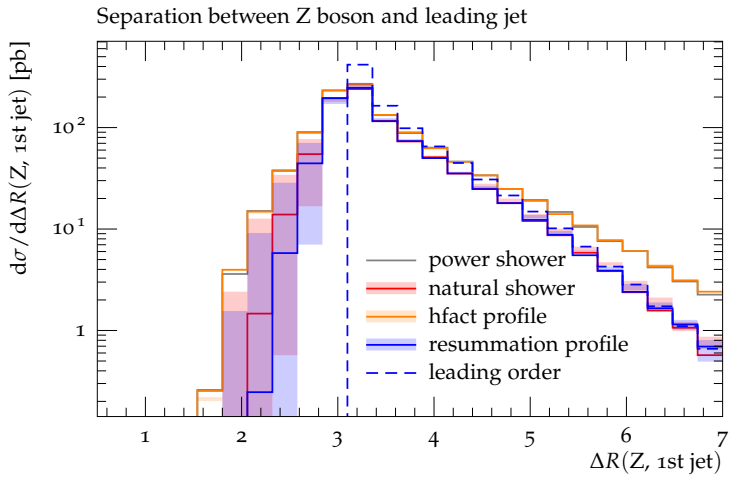
μ_Q variations and profile scales.

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



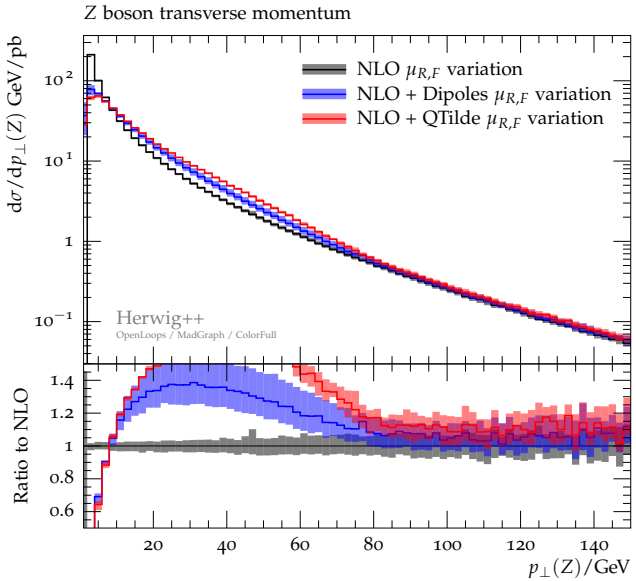


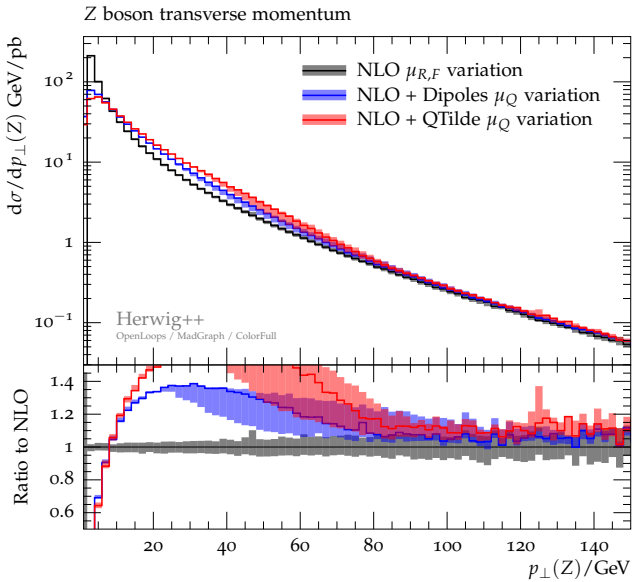




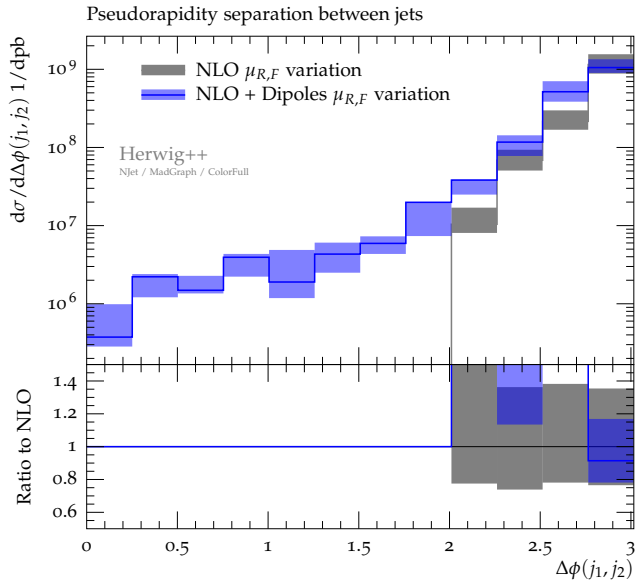
Full benchmark of uncertainties in progress – S. Gieseke & SP

Matching uncertainties.

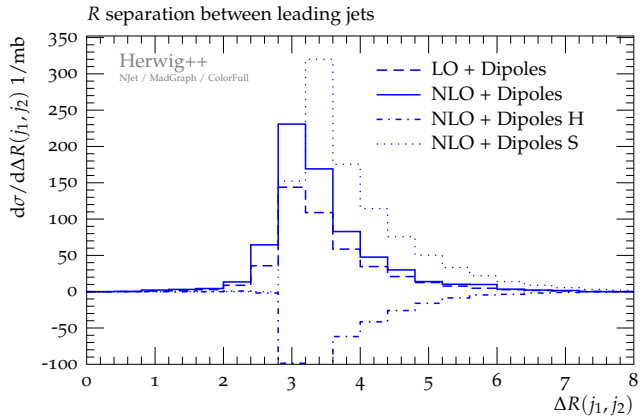




More (jetty) processes in progress, e.g. dijets:



Intricate pattern of cancellations in scale variations?



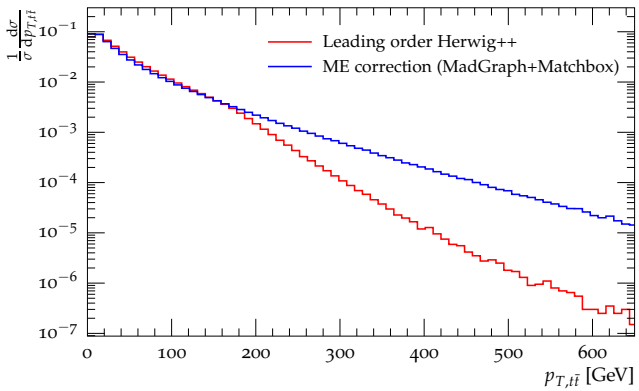
BSM with Matchbox.

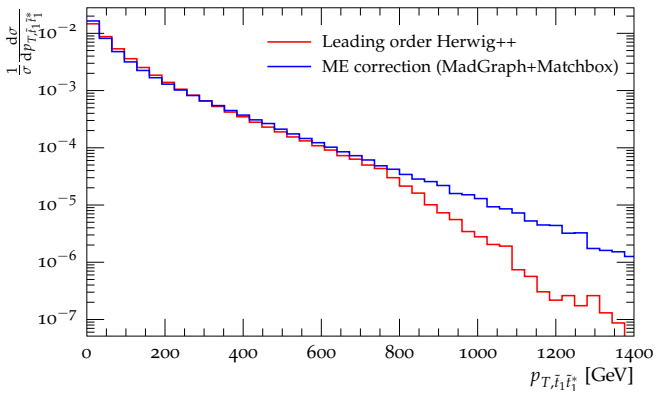
[A. Wilcock, P. Richardson, SP – work in progress]

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.





EW corrections.

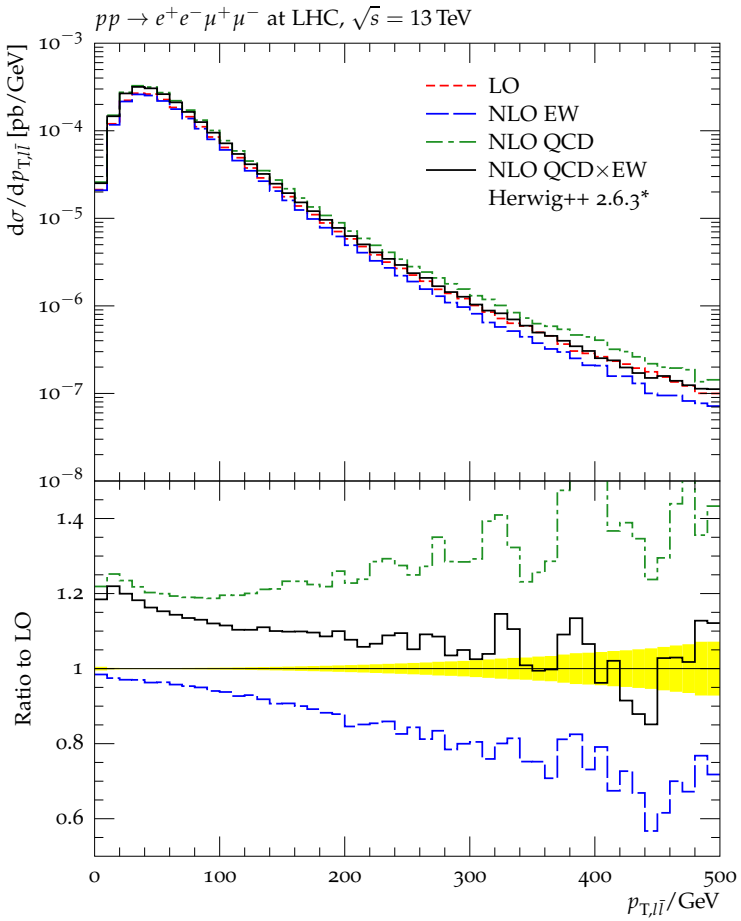
[S. Gieseke, T. Kasprczik, J. Kühn – arXiv:1401.3964]

Electroweak corrections to diboson production @ LHC.

- Factorized ansatz to mixed corrections:

  $$(1+\delta_{\text{QCD}})(1+\delta_{\text{EW}}) \approx 1+\delta_{\text{QCD}}+\delta_{\text{EW}}$$

- Valid if both corrections are small
  $\rightarrow$ use suitable cuts to supress phase space enhanced QCD corrections
- QCD corrections from builtin POWHEG cross sections
- EW corrections through $\hat{s}, \hat{t}$-dependent reweighting

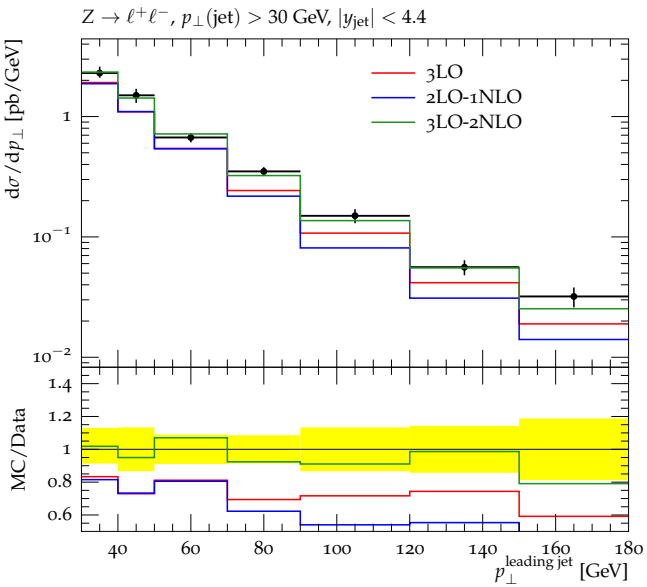


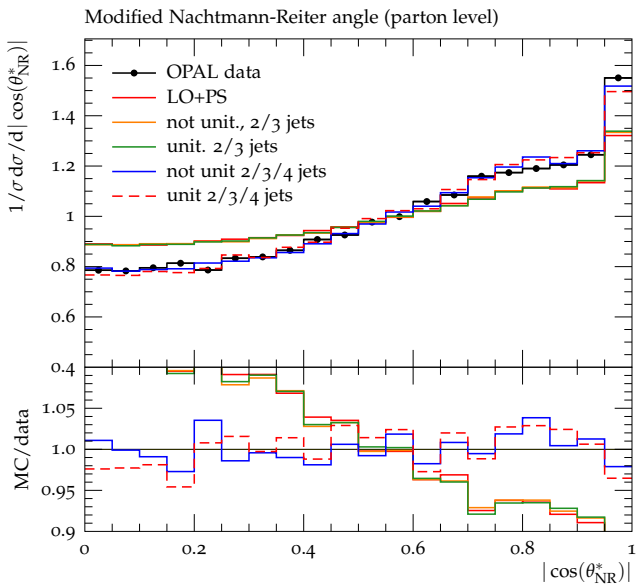
(N)LO Merging.

[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, four-jet correlations at LEP.

Summary & Outlook.

Current release: Dedicated approaches to NLO matching.
Largely hand-made or semi-automated, many processes available, well established.

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.
Not covered: Subleading-N improvements.

Matchbox 2.0 will appear with Herwig++ 2.8.0, partial beta tester in 2.7.1.
Stay tuned on `herwig.hepforge.org`