Higher-order QCD Improvements in Herwig++

Simon Plätzer

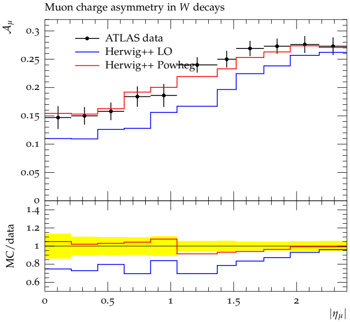
DESY

Outline.

- Overview.
- NLO Calculations with Matchbox.
- A Fresh Look at NLO Matching.
- (N)LO Merging.
- Conclusions & Outlook.

Overview.

Dedicated approaches to NLO matching, largely hand-made or semi-automated.



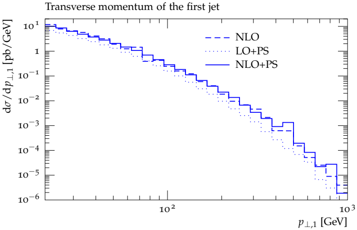
Muon charge asymmetry in W decays

$pp \to W$

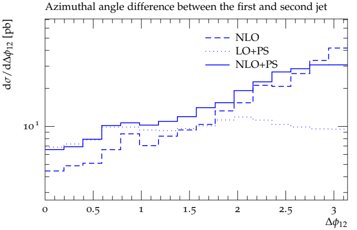
[K. Hamilton, J. Tully, P. Richardson – JHEP 0904 (2009) 116]

Z+jet

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



Transverse momentum of the first jet



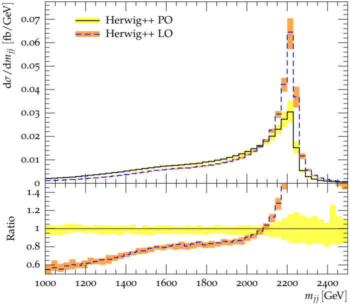
Azimuthal angle difference between the first and second jet

Dedicated NLO approaches: BSM Decay Chains.

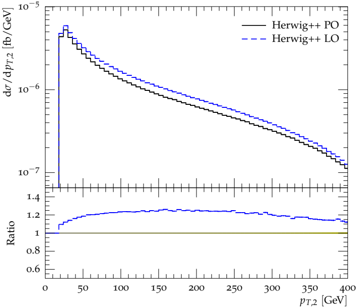
Powheg matching integrated with fexible and generic Herwig++ BSM infrastructure.

[P. Richardson, A. Wilcock – arXiv:1303.4563]

Jet pair mass in RS graviton decay.



$p_\perp$ distribution in CMSSM squark decay.



Overview.

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

Change in paradigm: Full automation, ultimately NLO by default.

Revisit some issues in NLO matching → more general algorithm, uncertainties.

NLO Calculations with Matchbox.

$$\begin{aligned}\sigma_{\mathrm{NLO}} = \int_n \mathrm{d}\sigma_{\mathrm{LO}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}_{n,0}|^2 \end{pmatrix} \quad &+ \quad \int_n \left[\mathrm{d}\sigma_{\mathrm{V}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle, |\mathcal{M}_{n,1}\rangle \\ 2\mathrm{Re}(\langle \mathcal{M}_{n,0}|\mathcal{M}_{n,1}\rangle) \end{pmatrix} + \int_1 \mathrm{d}\sigma_{\mathrm{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right] \\ &+ \quad \int_{n+1} \left[\mathrm{d}\sigma_{\mathrm{R}} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - \mathrm{d}\sigma_{\mathrm{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]\end{aligned}$$

Interfaces at amplitude level

- Color bases provided, including interface to `ColorFull`.
  [M. Sjödahl, SP]
- Spinor helicity library and caching facilities.
- Some in-house calculations and parts of `HJets++`.
  [F. Campanario, T. Figy, SP, M. Sjödahl]

Interfaces at squared amplitude level

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

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

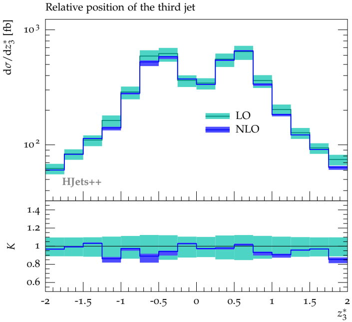
- Process generation and bookkeeping, integration, analysis.
- Automatic crossing if required, various caching facilities.
- Automated Catani-Seymour dipole subtraction, alternative choices possible.
- Diagram-based mutli-channel phase space, straightforward interface for alternatives.

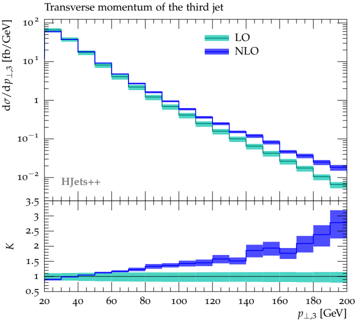
NLO Calculations with Matchbox.

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 → 4 process.
- Hybrid interfaces of amplitude and squared amplitude infrastructure, internal cross checks possible.


Relative position of the third jet


Transverse momentum of the third jet

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

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

NLO Matching.

Basic structure of NLO matching is settled. [Not even attempting a list of references.]

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}}\right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2)$$

$$\begin{aligned}
\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \quad = \quad & \left[\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n)\right] u(\phi_n) \\
+ \quad & \left[\mathrm{d}\sigma_{PS}(\phi_{n+1})\theta(q-\mu) - \mathrm{d}\sigma_A(\phi_{n+1}) \qquad\qquad\qquad \right] u(\tilde{\phi}_n) \\
+ \quad & \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1})\theta(q-\mu) \qquad\qquad\qquad \right] u(\phi_{n+1})
\end{aligned}$$

NLO Matching.

Basic structure of NLO matching is settled. [Not even attempting a list of references.]

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma^{\text{matched}}_{\text{NLO}}\right] = \mathrm{d}\sigma_{\text{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2)$$

$$\begin{aligned}
\mathrm{d}\sigma^{\text{matched}}_{\text{NLO}} &= \left[\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n)\right] u(\phi_n) \\
&+ \left[\mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad\qquad - \mathrm{d}\sigma_A(\phi_{n+1}) \qquad\qquad\qquad\qquad \right] u(\tilde{\phi}_n) \\
&+ \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad\qquad\qquad\qquad\qquad\qquad \right] u(\phi_{n+1})
\end{aligned}$$

NLO Matching.

Basic structure of NLO matching is settled. [Not even attempting a list of references.]

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2) + \mathcal{O}(1/N_c^2)$$

$$\begin{aligned} \mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} &= \left[\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n) \right] u(\phi_n) \\ &+ \left[\mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad - \mathrm{d}\sigma_A(\phi_{n+1}) + \mathrm{d}\sigma_{PS}^{\mathsf{repair}}(\phi_{n+1}) \right] u(\tilde{\phi}_n) \\ &+ \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad - \mathrm{d}\sigma_{PS}^{\mathsf{repair}}(\phi_{n+1}) \right] u(\phi_{n+1}) \end{aligned}$$

Ways out? → Improve shower for at least the first emission.

- Powheg-type matchings do not have these troubles.
- All correlations for the hardest emission. [S. Hoeche, F. Krauss, M. Schönherr, F. Siegert – JHEP 1209 (2012) 049]
- Use shower with colour matrix element corrections. [SP & M. Sjödahl –JHEP 1207 (2012) 042]

A Fresh Look at NLO Matching.

[SP – in preparation]

Are there other ways to get rid of the correlation problem?

- Accept the intrinsic limitation of IR cutoff effects.
- Use this freedom to cast the matched calculation into a different form:
  Very much inspired by recent work on NLO merging. [SP – JHEP 1308 (2013) 114]

$$\mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{matched}} = \mathrm{d}\sigma_{B+V+A}(\phi_n)u(\phi_n) + \mathrm{d}\sigma_{R-A}^{S} + \mathrm{d}\sigma_{R-A}^{E} + \mathrm{d}\sigma_{R}^{F}$$

Important to keep all details, particularly generation cuts.
Serves as input to merging for *e.g.* QCD jets.

A Fresh Look at NLO Matching.

[SP – in preparation]

Are there other ways to get rid of the correlation problem?

- Accept the intrinsic limitation of IR cutoff effects.
- Use this freedom to cast the matched calculation into a different form:
  Very much inspired by recent work on NLO merging. [SP – JHEP 1308 (2013) 114]

$$\mathrm{d}\sigma_{\text{NLO}}^{\text{matched}} = \mathrm{d}\sigma_{B+V+A}(\phi_n)u(\phi_n) + \mathrm{d}\sigma_{R-A}^{S} + \mathrm{d}\sigma_{R-A}^{E} + \mathrm{d}\sigma_{R}^{F}$$

$$\mathrm{d}\sigma_{R-A}^{S} = \left[1 - \prod_\alpha (1-\theta_{\text{cuts}}(\phi_n^\alpha))\right] \times \Bigg[\mathrm{d}\sigma_R(\phi_{n+1})\theta_{\text{cuts}}(\phi_{n+1})\left[1-\prod_\alpha \theta_\mu^\alpha(\phi_{n+1})\right]\sum_\alpha w_\alpha(\phi_{n+1})u(\phi_n^\alpha) - \sum_\alpha \left(\mathrm{d}\sigma_A^\alpha(\phi_{n+1}) - \mathrm{d}\sigma_{\text{PS}}^\alpha(\phi_{n+1})\theta_\mu^\alpha(\phi_{n+1})\right)\theta_{\text{cuts}}(\phi_n^\alpha)u(\phi_n^\alpha)\Bigg]$$

- Singular real emission below shower cutoff → full subtraction terms

Important to keep all details, particularly generation cuts.
Serves as input to merging for *e.g.* QCD jets.

A Fresh Look at NLO Matching.

[SP – in preparation]

Are there other ways to get rid of the correlation problem?

- Accept the intrinsic limitation of IR cutoff effects.
- Use this freedom to cast the matched calculation into a different form:
  Very much inspired by recent work on NLO merging. [SP – JHEP 1308 (2013) 114]

$$\mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{matched}} = \mathrm{d}\sigma_{B+V+A}(\phi_n)u(\phi_n) + \mathrm{d}\sigma_{R-A}^{S} + \mathrm{d}\sigma_{R-A}^{E} + \mathrm{d}\sigma_{R}^{F}$$

$$\mathrm{d}\sigma_{R-A}^{E} = \left[1 - \prod_{\alpha}(1-\theta_{\mathrm{cuts}}(\phi_n^{\alpha}))\right] \times \left[\mathrm{d}\sigma_R(\phi_{n+1})\theta_{\mathrm{cuts}}(\phi_{n+1})\prod_{\alpha}\theta_{\mu}^{\alpha}(\phi_{n+1}) - \sum_{\alpha}\mathrm{d}\sigma_{\mathrm{PS}}^{\alpha}(\phi_{n+1})\theta_{\mathrm{cuts}}(\phi_n^{\alpha})\theta_{\mu}^{\alpha}(\phi_{n+1})\right] u(\phi_{n+1})$$

- Singular real emission below shower cutoff → full subtraction terms
- Singular real emission above shower cutoff → shower subtraction only

Important to keep all details, particularly generation cuts.
Serves as input to merging for *e.g.* QCD jets.

A Fresh Look at NLO Matching.

[SP – in preparation]

Are there other ways to get rid of the correlation problem?

- Accept the intrinsic limitation of IR cutoff effects.
- Use this freedom to cast the matched calculation into a different form:
  Very much inspired by recent work on NLO merging. [SP – JHEP 1308 (2013) 114]

$$\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} = \mathrm{d}\sigma_{B+V+A}(\phi_n)u(\phi_n) + \mathrm{d}\sigma_{R-A}^{S} + \mathrm{d}\sigma_{R-A}^{E} + \mathrm{d}\sigma_{R}^{F}$$

$$\mathrm{d}\sigma_{R}^{F} = \mathrm{d}\sigma_{R}(\phi_{n+1})\theta_{\mathsf{cuts}}(\phi_{n+1})\prod_{\alpha}(1-\theta_{\mathsf{cuts}}(\phi_n^{\alpha}))u(\phi_{n+1}) \ .$$

- Singular real emission below shower cutoff → full subtraction terms
- Singular real emission above shower cutoff → shower subtraction only
- Finite, hard large-angle, real emission contribution → no shower

Important to keep all details, particularly generation cuts.
Serves as input to merging for *e.g.* QCD jets.

A Fresh Look at NLO Matching.

[SP – in preparation]

Are there other ways to get rid of the correlation problem?

- Accept the intrinsic limitation of IR cutoff effects.
- Use this freedom to cast the matched calculation into a different form:
  Very much inspired by recent work on NLO merging. [SP – JHEP 1308 (2013) 114]

$$\mathrm{d}\sigma_{\text{NLO}}^{\text{matched}} = \mathrm{d}\sigma_{B+V+A}(\phi_n)u(\phi_n) + \mathrm{d}\sigma_{R-A}^{S} + \mathrm{d}\sigma_{R-A}^{E} + \mathrm{d}\sigma_{R}^{F}$$

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma_{\text{NLO}}^{\text{matched}}\right] = \mathrm{d}\sigma_{\text{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2)$$

- Singular real emission below shower cutoff → full subtraction terms
- Singular real emission above shower cutoff → shower subtraction only
- Finite, hard large-angle, real emission contribution → no shower
- Same accuracy retained. Basically a phase space slicing.

Important to keep all details, particularly generation cuts.
Serves as input to merging for *e.g.* QCD jets.

Profiling the Hardest Emission.

[SP – in preparation]

Hard shower scale μ_Q ($\sim$ resummation scale) not coinciding with kinematic boundary. Important to resum the right logarithms in *e.g.* DY $p_\perp$ spectra.

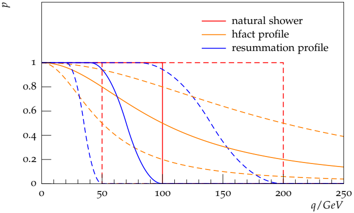
A problem in NLO matching:

$$|\mathcal{M}_B|^2 K_{\text{NLO}}(q < \mu_Q) P(q) \Delta(q|\mu_Q) \theta(\mu_Q - q) + |\mathcal{M}_R|^2 \theta(q - \mu_Q)$$

- Jump in q-spectrum even if $P(q)$ resembles full real emission matrix element.
- The jump is an NNLO effect.
- Clearly visible when shower scale coincides with physical quantity considered.
- Otherwise appears ‘somewhere’ → MVA’s?!

Cure by changing the hard step to something smooth.

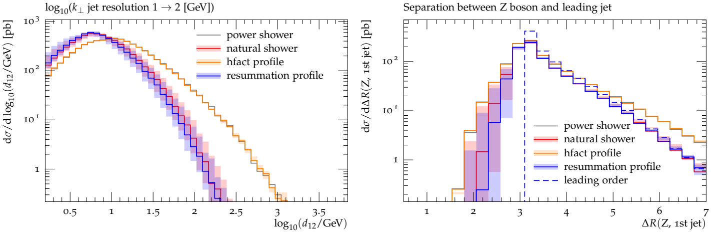
μ_Q variation intimately linked to shower uncertainties.



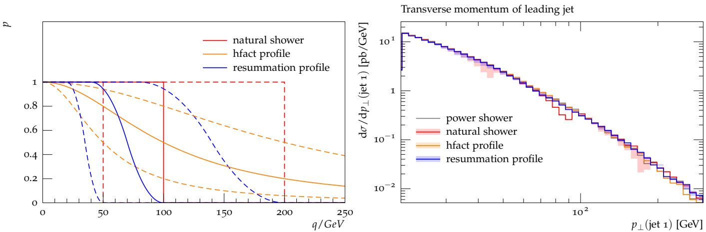
Profiling the Hardest Emission.

[SP – in preparation]

NLO matching may hide some features. Validate at LO, *e.g.* Z+jet

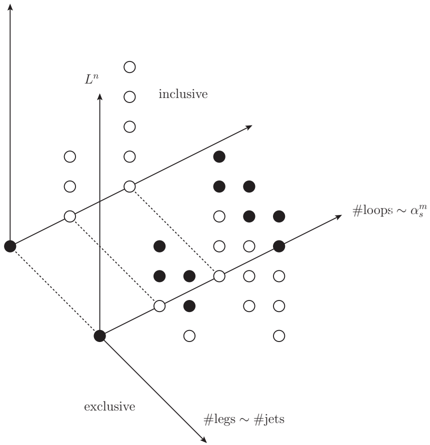


Step problem solved, *e.g.* dipole shower ($p_\perp$ ordering):



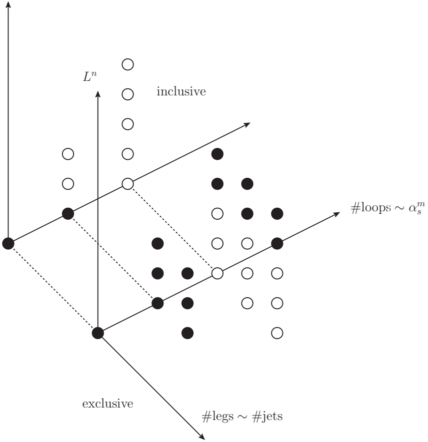
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms.
Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



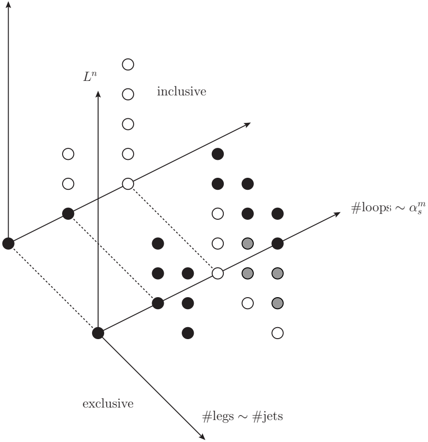
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms. Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



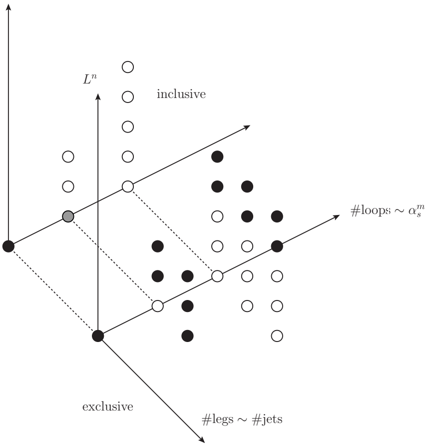
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms. Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



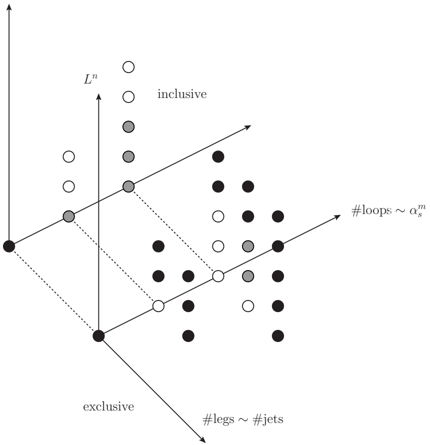
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms. Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



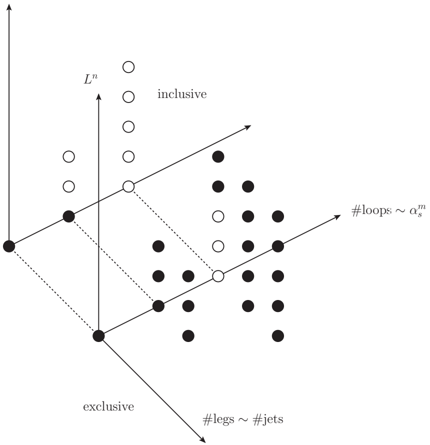
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms. Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



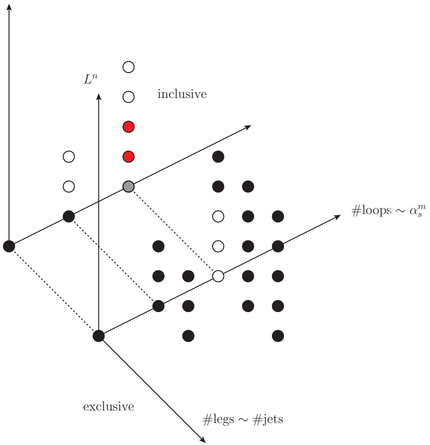
(N)LO Merging.

Matchbox framework provides unique possibilities for exploring new merging algorithms. Follow the ‘unitarized’ approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



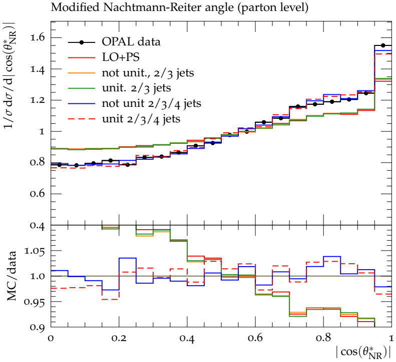
(N)LO Merging.

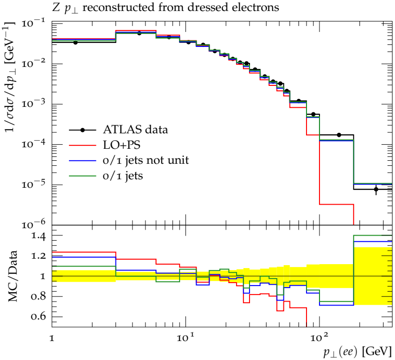
Matchbox framework provides unique possibilities for exploring new merging algorithms.
Follow the 'unitarized' approach. [SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]



The Merging Algorithm in Herwig++.

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


Modified Nachtmann-Reiter angle (parton level)


Z $p_\perp$ reconstructed from dressed electrons

Conclusions & Outlook.

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

Change in paradigm: Matchbox can automatically assemble NLO calculations.
Many interfaces to external amplitude providers, some builtin processes.

Revisited the NLO matching condition and uncertainties.
New matching paradigm and profile scales supported in a very modular way.

Matching support for dipole shower, Powheg-type matching.
Default shower in progress.

Matchbox 2.0β & much more out with Herwig++ release 2.7

J. Bellm, S. Gieseke, D. Grellscheid, A. Papaefstathiou, S. Plätzer, P. Richardson,
C. Röhr, T. Schuh, M.H. Seymour, A. Siodmok, A. Wilcock, B. Zimmermann – arXiv:1310.6877 [hep-ph]

`herwig.hepforge.org`