MC's, Matching and all that

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DESY

A loose collection of some recent work @ Herwig++

Outline.

- NLO calculations with Matchbox
- A fresh look at NLO matching
- Controlling inclusive cross sections in ME+PS merging
- Conclusions & Outlook

NLO Calculations with Matchbox.

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

$$+ \quad \int_{n+1} \left[\mathrm{d}\sigma_{\text{R}} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - \mathrm{d}\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$

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.

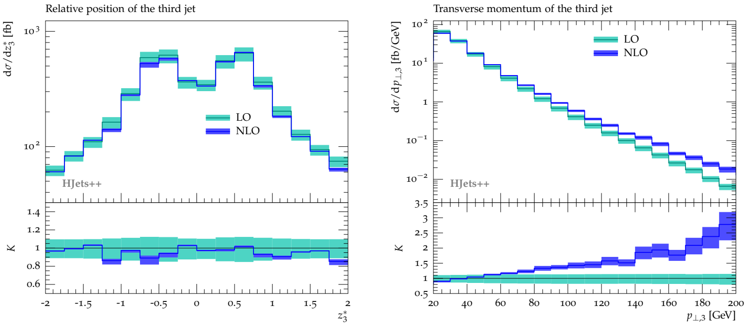
See Higgs session tomorrow for a recent application.

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.



$pp \to H + 3$ 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]

Some Aspects of NLO Matching.

[SP – in progress]

NLO Matching.

Basic structure of NLO matching is settled.

[Not even attempting a list of references.]

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

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

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

Ways out? $\rightarrow$ 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.

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.

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

- Singular real emission below shower cutoff $\rightarrow$ full subtraction terms

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

- Singular real emission below shower cutoff $\to$ full subtraction terms
- Singular real emission above shower cutoff $\to$ shower subtraction only

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

- 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.

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

- Singular real emission below shower cutoff $\to$ full subtraction terms
- Singular real emission above shower cutoff $\to$ shower subtraction only
- Finite, hard large-angle, real emission contribution $\to$ 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.

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.

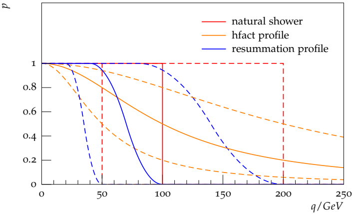
A problem in NLO matching:

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

- 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' $\rightarrow$ MVA's?!

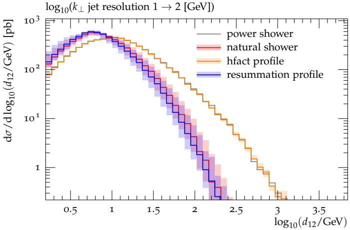
Cure by changing the hard step to something smooth.

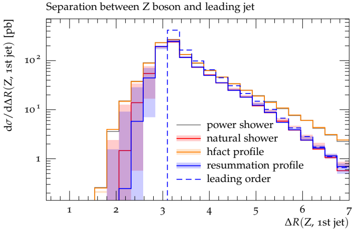
μ_Q variation intimately linked to shower uncertainties.



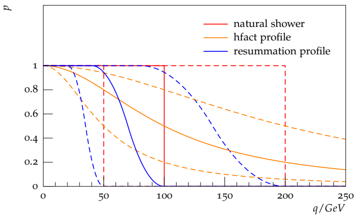
Profiling the Hardest Emission.

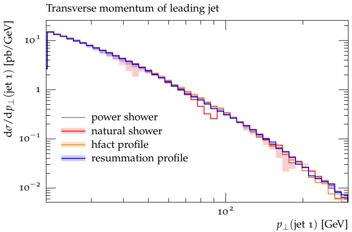
NLO matching may hide some features. Validate at LO, *e.g.* Z+jet





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

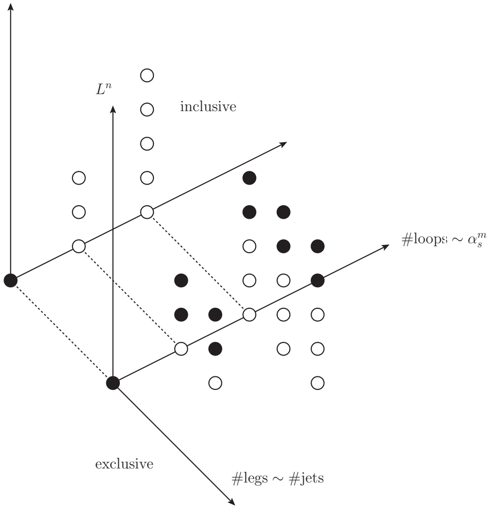




Controlling Inclusive Cross Sections in ME+PS Merging.

[SP – JHEP 1308 (2013) 114] [Lönnblad, Prestel]

Tree level merging.



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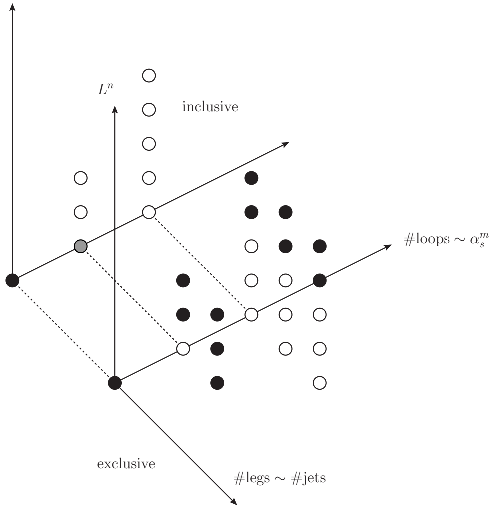

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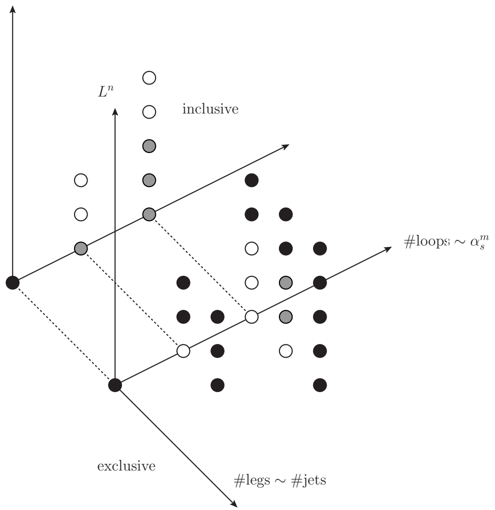


Tree level merging.

Merging condition: LO $\times$ products of splitting kernels $\to$ exact tree level ME.

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma^{\text{merged}}_{N,\mu}\right] = \sum_{k=0}^{N-1} \mathrm{d}\sigma^{(0)}_\mu(\phi_k, q_k)\Delta_k(\mu|q_k|\cdots|q_0) \ + \mathrm{PS}_\mu\left[\mathrm{d}\sigma^{(0)}_\mu(\phi_N, q_N)\Delta_{N-1}(q_N|\cdots|q_0)\right]$$

- Parton shower infrared cutoff applied to reclustered tree level matrix elements,
- proper Sudakov form factors to account for exclusiveness,
- no merging scale required in the first place.

Tree level merging.

Cut off matrix elements at $\rho > \mu$:

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma^{\mathsf{merged}}_{N,\rho} \right] =$$

$$\sum_{k=0}^{N-1} \mathrm{PS}_{\mu|\rho} \left[\mathrm{d}\sigma^{(0)}_\rho(\phi_k, q_k) \Delta_k(\rho|q_k|\cdots|q_0) \right] + \mathrm{PS}_\mu \left[\mathrm{d}\sigma^{(0)}_\rho(\phi_N, q_N) \Delta_{N-1}(q_N|\cdots|q_0) \right]$$

- 'Traditional' ME+PS merging, [CKKW, /Lönnblad, ...]
- no restriction on showering off the highest multiplicity.

Inclusive cross sections?

Exclusive cross sections are fine by the very definition of the merging condition.

Inclusive cross sections are generally spoiled, say $\geq N-1$ (parton shower) jets:

$$\mathrm{d}\sigma^{(0)}_\rho(\phi_{N-1}, q_{N-1})\Delta_{N-2}(q_{N-1}|\cdots|q_0)+$$
$$\int_\rho^{q_{N-1}} \mathrm{d}q_N \left(\frac{\mathrm{d}\sigma^{(0)}_\rho(\phi_N, q_N)}{\mathrm{d}q_N} - \frac{\mathrm{d}\phi_N}{\mathrm{d}\phi_{N-1}\mathrm{d}q_N} P_\rho(\phi_{N-1}, q_N)\mathrm{d}\sigma^{(0)}_\rho(\phi_{N-1}, q_{N-1}) \right) \times$$
$$\Delta_{N-1}(q_N|\cdots|q_0)$$

Natural consequence of replacing splitting kernels by matrix elements *except for the Sudakov exponents.* [cf. matrix element correction approaches like Vincia, Skands et al.]

Not a problem as long as the shower kernels approximate the singly-unresolved limits of the *tree level matrix elements* sufficiently good.

From nLO merging to NLO merging.

Constrain the matching condition to preserve inclusive cross section:
Except for the highest multiplicity, replace

$$\mathrm{d}\sigma_\rho^{(0)}(\phi_k, q_k) \to \mathrm{d}\sigma_\rho^{(0)}(\phi_k, q_k) - \int_\rho^{q_k} \mathrm{d}q_{k+1} \frac{\mathrm{d}\sigma_\rho^{(0)}(\phi_{k+1}, q_{k+1})}{\mathrm{d}q_{k+1}} \Delta_k(q_{k+1}|q_k)$$

Fixed order expansion is a variant of the LoopSim nLO exclusive k jet cross section.

[Rubin, Salam, Sapeta – 1006.2144]

After showering we get precisely this contribution with the proper Sudakov supression.

LO merging with inclusive cross sections preserved → nLO merging.

From nLO merging to NLO merging.

Replace the nLO approximate α_s correction by the NLO exact α_s correction.

In a nutshell: Where available add

$$\mathrm{PS}_\rho^{-1}\left[\left(\mathrm{d}\sigma_\rho^{(1)}(\phi_n, q_n) + \int_0^{q_n} \mathrm{d}q_{n+1} \frac{\mathrm{d}\sigma^{(0)}(\phi_{n+1}, q_{n+1})}{\mathrm{d}q_{n+1}} \theta(q_n - \rho)\right) \Delta_{n-1}(q_n|\cdots|q_0)\right]$$

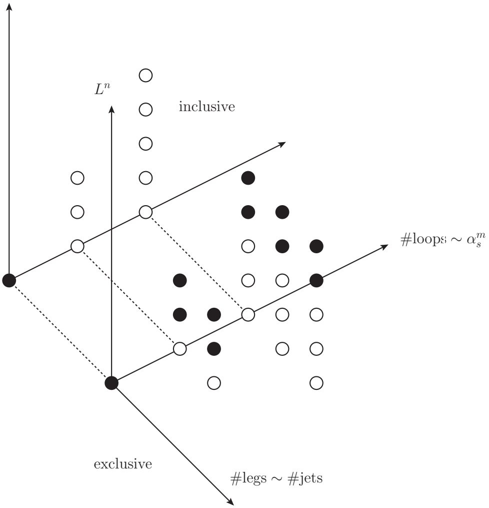
to the merged cross section.

This is NLO merging, as recently discussed in several variants.

[Höche et al. – 1207.5030, Frederix, Frixione – 1209.6215, Lönnblad, Prestel – 1211.7278, Hamilton et al. – 1212.4504]

– Recover exclusive NLO n-jet cross sections above the merging scale.
– NLO accuracy below the merging scale by constrained NLO matching.

The landscape for NLO merging.



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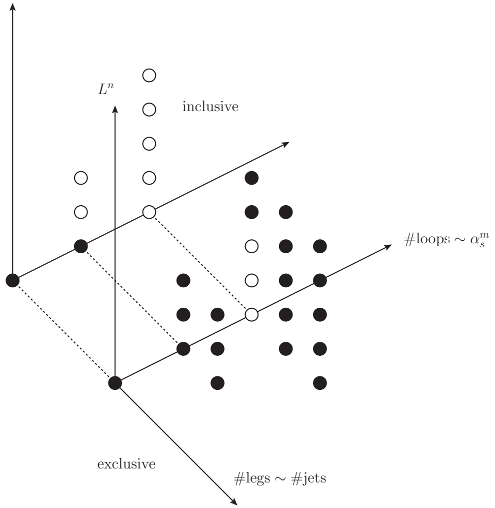

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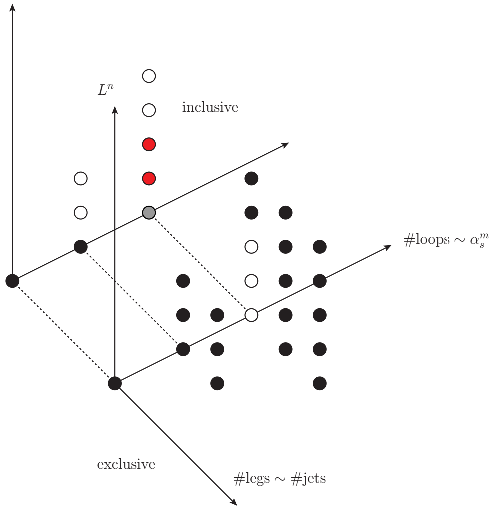
$$\mathrm{d}\sigma^{\mathsf{NLO}}_{\rho,\mathsf{incl}}(\phi_{N-1}, q_{N-1})\Delta_{N-2}(q_{N-1}|\cdots|q_0)+$$
$$\int_\rho^{q_{N-1}} \mathrm{d}q_N \left(\frac{\mathrm{d}\sigma^{\delta\mathsf{NLO}}_{\rho,\mathsf{excl}}(\phi_N, q_N)}{\mathrm{d}q_N} - \frac{\mathrm{d}\phi_N}{\mathrm{d}\phi_{N-1}\mathrm{d}q_N} P_\rho(\phi_{N-1}, q_N)\mathrm{d}\sigma^{\delta\mathsf{NLO}}_{\rho,\mathsf{excl}}(\phi_{N-1}, q_{N-1}) \right) \times$$
$$\Delta_{N-1}(q_N|\cdots|q_0)$$

Similar to the tree level problems.

But now a serious problem unless we have a shower which knows about the singly unresolved limits of *virtual contributions*.

The landscape for NLO merging.

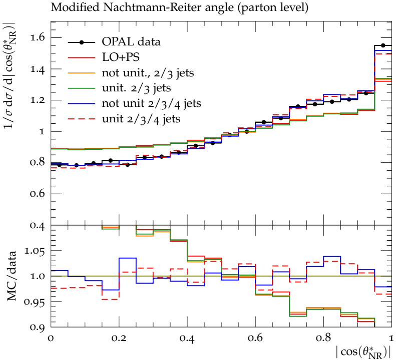


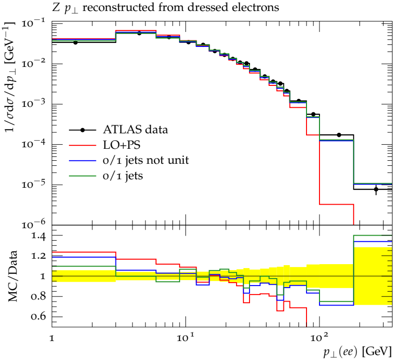
Subtract critical terms by imposing NLO inclusive cross section constraints.

Generates approximate NNLO contribution $\rightarrow$ guide to NNLO matching.

The Merging Algorithm in Herwig++.

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





Conclusions & Outlook.

Establishing NLO as default accuracy in Herwig++

- Matchbox provides a framework for automatically asembling NLO cross sections
- More general matching algorithm established, including profile scales
  $\rightarrow$ uncertainties
- Merging multiple NLO calculations in progress
  $\rightarrow$ maintain inclusive quantities at NLO accuracy

Not covered

- Development on including subleading-N contributions