NLO + Parton Showers merging: current status and future perspectives

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Key messages:

- This is a very rapidly evolving field, with many new methods being introduced or improved
- in 20’ impossible to give a complete overview: certainly I forgot something: I apologise for this
- Monte Carlo tools are widely used:
  → impact of all these improvements likely important for LHC Physics
  (think about the impact that MC@NLO and POWHEG had during LHC Run I)
Introduction and outline

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  - impact of all these improvements likely important for LHC Physics
    (think about the impact that MC@NLO and POWHEG had during LHC Run I)

Outline:
- status and improvements in parton showers
- NLO matching (NLO+PS)
- NLO multijet merging
- NNLO matching (NNLO+PS)
- conclusions and outlook
Parton Showers & LO+PS
LO+parton showers

parton-shower (PS) programs: backbones for all approaches that go beyond fixed-order accuracy, simulating fully exclusive events (including hadronisation, MPI,...)

- PS programs currently used for LHC Physics: Pythia8, Herwig++, Sherpa
  - based on factorisation of QCD amplitudes
  - accuracy: LL, leading colour (planar)
  - some NLL/subleading colour effects included
  - differences in ordering variable, splitting kernels and recoiling scheme

- other approaches exist (Ariadne, Vincia, KRK)
- ongoing activity also to improve PS algorithms
  - subleading-N effects
  - interference effects
  - EW showers

[Plätzer, Sjödahl '13]
[Nagy, Soper '14]
[Christiansen, Sjöstrand / Krauss, Petrov et al '14]
LO+parton showers

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 Beyond LO+PS

- standalone Monte Carlo are LO+(N)LL accurate (LO+PS)
- name of the game: improve the accuracy of Monte Carlo programs including as much information as possible from higher-order perturbative QCD (from fixed order, but also from resummation)

- this has to be done consistently: the “less accurate” approach we want to improve already includes some approximation of the terms we want to include exactly:
• standalone Monte Carlo are LO+(N)LL accurate (LO+PS)
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- will talk about recent progress in NLO+PS tools (POWHEG, MC@NLO,...) and improvements thereof ("NLOPS multijet merging", "NNLO+PS")
matching NLO and PS (NLO+PS)
NLO matching (NLO+PS)

- MC@NLO [Frixione,Webber ’02] and POWHEG [Nason’04] are by now well established: method of choice when available
- if a QCD NLO computation for \( pp \rightarrow X \) exists [by now it probably does, see S. Badger talk], it can be (was) matched to a PS
  - inclusive observables at NLO
    \[ \text{normalisation starts to stabilise, meaningful assessment of theoretical uncertainties, K-factors included } \]
  - (N)LL Sudakov resummation where relevant
  - large-\( p_T \) hardest associated jet at LO
  - extra jets at LL
  - fully exclusive events

- \( X \) can contain jets
  (but if it contains \( N \)-jets, not possible to describe observables with \( n < N \) jets)

<table>
<thead>
<tr>
<th>available tools:</th>
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<tr>
<td><strong>POWHEG based</strong>: POWHEG-BOX, PowHel, Matchbox/Herwig++</td>
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<td><strong>MC@NLO based</strong>: MG5_aMC@NLO, Sherpa-MC@NLO, Matchbox/Herwig++</td>
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<td>- HEJ</td>
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<td>- Geneva</td>
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<td>- KRK</td>
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[Anderersen, Hapola, Smillie]
[Giele, Kosower, Skands, et al]
[Alioli, Bauer, et al ’12]
see S. Sapeta talk this session
NLO matching (POWHEG)

- **POWHEG-BOX** [Alioli,Nason,Oleari,ER,Hamilton,Zanderighi + many others involved]
  (http://powhegbox.mib.infn.it/)
- **pure QCD**: $jj$, $jjj$
- **EW**: $V(\pm j, \pm jj)$, $VV$, $Wb\bar{b}$, $W^+ W^+ jj$ (QCD)
- **top**: $t\bar{t}(+j)$, $tj$ ("single top", also in 4f scheme), $tW$
- **VBF**: $Vjj$, $VVjj$
- **Higgs**: $H(\pm j, \pm jj)$, $HV$, $HV_j$, $Hjj$ (VBF), $Hjjj$ (VBF)
- **BSM**: $tH^+$, $\tilde{\ell}\tilde{\ell}$, $\tilde{q}\tilde{q}$, $H/A$ in MSSM, DM+monojets
- **QED/EW & QCD**: Drell-Yan

- **PowHel** [Garzelli,Kardos,Papadopoulos,Trócsányi]
  (http://grid.kfki.hu/twiki/bin/view/DbTheory/WebHome)
- **top pairs**: $t\bar{t}$, $t\bar{t}j$, $t\bar{t}H$, $t\bar{t}V$, $t\bar{t}b\bar{b}$, $W^+ W^- b\bar{b}$

**POWHEG-BOX (V2):**
- th. uncertainty: fast PDF and scale reweighting
- can use MadGraph4 for all tree-level terms
- can be interfaced to 1-loop codes (HELAC, MCFM, GoSam, NLOJET++), supports BLHA
- possible to generate at NLO+PS also correction to decay of heavy resonances
- validation and phenomenology for $t\bar{t}$ in progress [Nason,Campbell,Ellis,ER, in progress]
NLO matching (POWHEG)

$pp \rightarrow Hjjjj \ (VBF)$

[Jäger, Schissler, Zeppenfeld '14]

$\rightarrow W^+ W^- b\bar{b}$ (5f-scheme)

[Garzelli, Kardos, Trócsányi '14]

- amplitudes from VBFNLO
- estimate uncertainties due to “Central Jet Veto” techniques

$\frac{d\sigma}{dp_{T,j3}} \ [pb/GeV]$

$\frac{d\sigma}{dp_{T,j3}} \ [pb/GeV]$

$pp \rightarrow Hjjjj \ (VBF)$

$\rightarrow W^+ W^- b\bar{b}$ (5f-scheme)

[Garzelli, Kardos, Trócsányi '14]

- fully differential $tt$ as signal and background
- exact handling of offshellness effects by PS need be addressed in this context
NLO matching (aMC@NLO)

- MadGraph5_aMC@NLO [Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro]
  (http://amcatnlo.web.cern.ch/amcatnlo/)

  milestone in 2014 for the QCD/MC community:
  - essentially all $2 \to 4$ processes you can think about (and also $e^+ e^-$)
  - several of these processes were never computed before

- embedded in Madgraph5
- fully automated (thanks to MadFKS and MadLoop)
- th. uncertainty: fast PDF and scale reweighting
- will soon allow also EW corrections and BSM models, thanks to interface to FeynRules
  [Alloul,Christensen,Degrande,Duhr,Fuks]

  - NLO EW & NLO QCD effects for $t\bar{t}H$
    [Frixione,Hirschi,Pagani,Shao,Zaro, this week]
NLO matching (aMC@NLO)

\[ pp \rightarrow H H X \]

[Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro]

\[ pp \rightarrow e^+ e^- \mu^+ \nu_\mu \tau^+ \nu_\tau \]
NLO matching (Sherpa-MC@NLO)

- **Sherpa-MC@NLO**

  - interfaced to 1 loop codes, typically with BLHA (BlackHat, OpenLoops, GoSam, MCFM)
  - traditionally focussed on $S + \text{jets} \ (S = V, VV, H)$
  - enormous progress over last 2 years; in particular:
    - NLO+PS multijet merging (MEPS@NLO)
    - thorough assessment of uncertainties

- $pp \rightarrow W + \text{jets}$ [NLO merging]
- $e^+ e^- \rightarrow \text{jets}$ [NLO merging]
- $pp \rightarrow H + \text{jets}$ [NLO merging]
- $pp \rightarrow t\bar{t} + \text{jets}$ [NLO merging]
- $pp \rightarrow 4\ell + \text{jets}$ [NLO merging]
- $pp \rightarrow VH/VV/VVV + \text{jets}$ [NLO merging]
- $pp \rightarrow t\bar{t}bb\ (4f)$ [NLO+PS]

[Cascioli,Gehrmann,Hoeche,Huang,Krauss,Luisoni,Maierhöfer, Pozzorini,Schoenherr,Siegert,Thompson,Winter,Zapp '13-'14]
NLO matching in Herwig++

- some processes available internally, in \textit{POWHEG} approach
  [Richardson, Hamilton, d’Errico, Fridman-Rojas, Tully, Wilcock]

- \textbf{Matchbox}: new standard for NLO+PS within \textit{Herwig++} (https://herwig.hepforge.org/)
  [Gieseke, Plätzter, Bellm, Fischer, Rauch, Reuschle, Wilcock, Richardson]

- general and modular framework to do NLO+PS matching within \textit{Herwig++}:
  - with \textit{POWHEG} and \textit{MC@NLO} schemes
  - using angular-ordered or dipole shower
  - focus also on assessment of uncertainties

- recently used to perform state-of-the-art NLO computation: \textit{H_{jjjj}} (VBF)
  [Campanario, Figy, Plätzter, Sjödahl ’13]

- currently being interfaced to NLO codes, also via BLHA
  (GoSam, Njet, VBFNLO, OpenLoops)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{jet_multiplicity.png}
\caption{Inclusive jet multiplicity $\sigma(\geq N_{\text{jet}})$ [pb]}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ratio.png}
\caption{Ratio NLO $\mu_R$ variation to dipoles/NLO $\mu_Q$ variation \textit{qtilde}/NLO $\mu_Q$ variation}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nlo_plus_ps_dijets.png}
\caption{NLO+PS dijets [preliminary]}
\end{figure}
NLO multijet merging
typical background for many BSM signatures is “heavy object” + many jets

relying on PS for tail of distributions is very dangerous, especially in a multijet environment

CKKW(-L) and MLM methods address this issue at LO:
- merge exact LO matrix elements for different multiplicities
- very important for observables like $H_T$
especially when not possible to use data-driven methods

suppose LHC finds a small excess in $H_T$ for some SUSY search (e.g. $E_T$ + jets)
- what is the theoretical uncertainty of backgrounds?
challenge: extend these methods to NLO ("NLOPS multijet merging"):  
- from one single event sample, have 1-, 2-,...,n-jet observables at NLO

at NLO it is more complicated, and more subtle:  
- the matrix element $pp \rightarrow S + n$ partons enters in  
  * Born for "$pp \rightarrow S + n$ partons" @ NLO  
  * real contribution for "$pp \rightarrow S + (n - 1)$ partons" @ NLO

as is at LO, many of these methods use a merging scale ($Q_{MS}$)  
- a bad choice of merging scale can spoil formal accuracy one might want to claim  
  * typically this can happen if $\alpha_S \log^2 Q_{MS} \simeq 1 \rightarrow L \simeq 1/\sqrt{\alpha_S}$

- in general, to avoid this problem, one needs not to have $Q_{MS}$ at all, or have a very precise control on formal accuracy of underlying resummation (typically beyond PS), so that even if $\alpha_S \log^2 Q_{MS} \simeq 1$, the formal accuracy is not spoiled

- to which extent this is a serious problem is still an open issue
proof of concept in $e^+e^-$ and $W+$ jets, applied in several other processes
- share some similarities with "FxFx"

\[
d\sigma = d\Phi_0 \vec{B}_0^{(A)} \otimes \tilde{P}\tilde{S}_{t_{\text{min}}} \Theta(d_1 < Q_{\text{MS}}) \\
+ d\Phi_1 H_0^{(A)} \Delta t_1 \Theta(d_1 < Q_{\text{MS}}) \\
+ d\Phi_1 \vec{B}_1^{(A)} \otimes \tilde{P}\tilde{S}_{t_{\text{min}}}^t \cdot \text{[corr. factor]} \cdot \Theta(d_1 > Q_{\text{MS}}) \\
+ d\Phi_2 H_1^{(A)} \Delta t_2 \Delta t_{t_{\text{min}}} \Theta(d_1 > Q_{\text{MS}})
\]

- possible to iterate to higher multiplicities
- residual dependence of total cross section on merging scale $\sim \alpha_S^2 L^3 / N_C^2$
\begin{align*}
\bar{d}\sigma_{S,0} &= T_0 + V_0 - T_0 K + T_0 K_{MC} \Theta(d_1 < Q_{MS}) \\
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\end{align*}
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- limit contribution of \((H,0)\) events to region below \(Q_{MS}\)
- prescriptions for shower starting scale
- possible to include Sudakov reweighting à la CKKW
- “unitarity” not imposed
- possible to iterate
FxFx method

\[ d\bar{\sigma}_{S,0} = T_0 + V_0 - T_0 \mathcal{K} + T_0 \mathcal{K}_{MC} \Theta(d_1 < Q_{MS}) \]
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- fully inclusive result:
  - differences typically \(\lesssim 1\%\) among different merging scales
  - quite good agreement with inclusive NLO+PS too
keyword: “unitarity” (preserve NLO inclusive cross section)

- method: promote to NLO accuracy an “unitarised” CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate $\alpha_S$ terms:
  1. start from UMEPS merging at LO

$$\langle \mathcal{O} \rangle = \int d\phi_0 \left\{ \mathcal{O}(S_{+0j}) \left( \mathcal{B}_0 + \int \mathcal{B}_1 \rightarrow 0 - \int \mathcal{B}_2 \rightarrow 0 \right) + \int_0 \mathcal{O}(S_{+1j}) \left( \mathcal{B}_1 - \int \mathcal{B}_2 \rightarrow 1 \right) \right\}$$

2. remove terms that will be included exactly, and add NLO (exclusive) computations

3. unitarise

$$\langle \mathcal{O} \rangle = \int d\phi_0 \left\{ \mathcal{O}(S_{+0j}) \left( \tilde{\mathcal{B}}_0 - \int_s \tilde{\mathcal{B}}_1 \rightarrow 0 + \int_s \mathcal{B}_1 \rightarrow 0 - \left[ \int \tilde{\mathcal{B}}_1 \rightarrow 0 \right]_{-2} - \int_s \mathcal{B}_2 \rightarrow 0 - \int \tilde{\mathcal{B}}_2 \rightarrow 0 \right) + \int_0 \mathcal{O}(S_{+1j}) \left( \tilde{\mathcal{B}}_1 + \left[ \tilde{\mathcal{B}}_1 \right]_{-1,2} - \left[ \int \tilde{\mathcal{B}}_2 \rightarrow 1 \right]_{-2} \right) \right\} + \int \int \mathcal{O}(S_{+2j}) \tilde{\mathcal{B}}_2$$

- can be iterated to higher multiplicities
- essentially no dependence on merging scale
“Multiscale Improved NLO” [Hamilton,Nason,Oleari,Zanderighi ’12]

- original goal: method to a-priori choose scales in multijet NLO computation
  (in a multiscale process, this is not straightforward, in regions with widely-separated scales)

- idea: correct weights of different NLO terms with CKKW-inspired approach
  (without spoiling formal NLO accuracy)
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\[
\bar{B}_{\text{NLO}} = \alpha_s^3(\mu_R) \left[ B + \alpha_s^{(NLO)} V(\mu_R) + \alpha_s^{(NLO)} \int d\Phi_{\text{rad}} R \right]
\]

\( \bar{B}_{\text{MiNLO}} \) ideal to extend validity of \( H+j \) POWHEG
- including terms from NNLL resummation, NLO+PS merging for 0 and 1-jet, without a merging scale. However:
  for now not clear how to extend to higher multiplicity

Sudakov FF included on \( H+j \) Born kinematics
- finite results if 1st jet unresolved

\[ m_h \]
\[ q_T \]
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\]

\[
\bar{B}_{MiNLO} = \alpha_s^2(m_h) \alpha_s(q_T) \Delta^2_g(q_T,m_h) \left[ B \left( 1 - 2\Delta_g^{(1)}(q_T,m_h) \right) + \alpha_s^{(NLO)} V(\bar{\mu}_R) + \alpha_s^{(NLO)} \int d\Phi_{rad} R \right]
\]

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\[
\bar{B}_{\text{NLO}} = \alpha_3^3(\mu_R) \left[ B + \alpha_s^{(\text{NLO})} V(\mu_R) + \alpha_s^{(\text{NLO})} \int d\Phi_{\text{rad}} R \right] \\
\bar{B}_{\text{MiNLO}} = \alpha_2^2(m_h) \alpha_s(q_T) \Delta_g^2(q_T, m_h) \left[ B \left( 1 - 2 \Delta^{(1)}(q_T, m_h) \right) + \alpha_s^{(\text{NLO})} V(\bar{\mu}_R) + \alpha_s^{(\text{NLO})} \right] \int d\Phi_{\text{rad}} R
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\( \Delta(q_T, m_h) \) Sudakov FF included on \( H+j \) Born kinematics

\( \Delta(q_T, q_T) \) finite results if 1st jet unresolved
Notice: band is $\sim 20 - 30\%$ (typical uncertainty for Higgs production at NLO)
new approach, SCET inspired [Alioli,Bauer,Berggren,Hornig,Tackmann,Vermilion,Walsh,Zuberi '12]

idea: separate exclusive $N$-jet and inclusive $(N+1)$-jet regions using variable whose resummation is known at high order (“n-jettiness”)

\[
\sigma \geq N = \int d\Phi_N \frac{d\sigma}{d\Phi_N}(T_N^{\text{cut}}) + \int d\Phi_{N+1} \frac{d\sigma}{d\Phi_{N+1}}(T_N) \theta(T_N > T_N^{\text{cut}})
\]

where

\[
\frac{d\sigma}{d\Phi_N}(T_N^{\text{cut}}) = \frac{d\sigma_{\text{resum}}}{d\Phi_N}(T_N^{\text{cut}}) + \left[ \frac{d\sigma_{\text{FO}}}{d\Phi_N}(T_N^{\text{cut}}) - \frac{d\sigma_{\text{resum}}}{d\Phi_N}(T_N^{\text{cut}}) \right]_{\text{FO}},
\]

\[
\frac{d\sigma}{d\Phi_{N+1}}(T_N) = \frac{d\sigma_{\text{FO}}}{d\Phi_{N+1}}(T_N) \left[ \frac{d\sigma_{\text{resum}}}{d\Phi_N dT_N} \right]_{\text{FO}},
\]

- no “dangerous” merging scale dependence, thanks to higher-order resummation for $\tau_N$
- to retain formal accuracy, PS evolution very constrained: $\tau_N$ has to stay $\sim$ unchanged
- can be extended to higher multiplicities
- implemented for $e^+e^-$, for LHC will be finished soon
  - talks by Alioli and Bauer at “PSR2014”
  - [link]
NNLO+PS
some of the above approaches allow(ед) to achieve \textbf{NNLO+PS} matching!

- “just” NLO sometimes is not enough
- NNLO is the frontier

already relevant: large NLO K-factor (Higgs production), precision Physics (PDF extraction, $W$-mass measurement), ...

more and more relevant for Run II and high-luminosity phase
NNLO+PS results

- **Higgs** [Hamilton,Nason,ER,Zanderighi ’13] and **Drell-Yan** [Karlberg,ER,Zanderighi (soon public)], using MiNLO-improved POWHEG

charged DY (left): find exactly what we expect: $p_T, \ell$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$

- Higgs $p_T$ (right): good agreement with NNLL+NNLO analytic resummation [HqT, Bozzi et al.]
- **Drell-Yan**, using **UNNLOPS**

  [Hoeche,Li,Prestel '14]

- **general framework and preliminary results for Drell-Yan also with Geneva**  
  [Alioli,Bauer, et al]
conclusions

- Monte Carlo tools play a major role for LHC searches
- especially if no “smoking gun” new-Physics around the corner, **precision** will be the key to maximise impact of LHC results
- huge amount of improvements over the last few years in the community
- part of this was possible due to impressive progress in NLO tools (**automation**), and development of standard interfaces (BLHA) between different codes

- **NLO+PS** tools are by now well established and very mature
  - important work still ongoing to tackle subtleties
- major developments in last 2 years: **NLOPS multijet merging**
  - accurate comparisons will take place, as it was for NLO+PS programs
- **NNLO+PS** is doable!
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Thank you for your attention!