Introduction Tree-level matching NLO Matching





Matching and Merging Overview

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 Introduction
 The perturbative QCD expansion

 Tree-level matching
 Parton Showers

 NLO Matching,
 Exclusive jet cross sections

Outline

- Introduction
- Tree-level matching
- NLO-Matching
- Discussion



Introduction The perturbative QCD expansion Tree-level matching Parton Showers NLO Matching Exclusive jet cross sections

Perturbative QCD prediction for an observable

$\alpha_s \rightarrow \alpha_s(\mu_R)$ can be reabsorbed into C_i but residual dependence if series is cut off.

Any jet observable will have an additional resolution scale giving a dependence of C_i on the logarithm $L = \log \mu_R / q_I$

We clearly have a problem if $L^2 lpha_{
m s} \sim$ 1

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Perturbative QCD prediction for an observable

 $\alpha_s \rightarrow \alpha_s(\mu_R)$ can be reabsorbed into C_i but residual dependence if series is cut off.

Any jet observable will have an additional resolution scale, ρ_{τ} giving a dependence of C_i on the logarithm $L = \log \mu_B / \rho_{\tau}$

We clearly have a problem if $L^2 lpha_{
m s} \sim 1$

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Perturbative QCD prediction for an observable

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For any non-inclusive observable we may get large logarithms and it is not enough to go to NLO, we also need to resum terms $\propto L^{2n}\alpha_s^n$ (LL) and maybe even $L^{2n-1}\alpha_s^n$ (NLL) or higher.

And then we need to worry about non-perturbative effects.

For a given observable we can use analytic resummation techniques and for some of these there are also analytic techniques for calculating *power corrections*.

The same thing is done in event generators with Parton Showers and hadronization models.

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Parton Showers

Start from a simple hard $(2 \rightarrow 2)$ scattering. Dress it with an arbitrary number of extra partons so that any observable will be correct to leading logarithmic (LL) accuracy.

Most parton showers will also resum some NLL-contributions, but typically only in the leading-colour approximation, $N_C \rightarrow \infty$.



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 No-emission probabilities

Exclusive *n*-jet cross section, Parton Shower style

$$d\sigma_n^{ex} = F_0 |\mathcal{M}_0|^2 d\phi_0 \times \left[\prod_{i=1}^n \alpha_s \frac{F_i}{F_{i-1}} P_i d\rho_i dz_i \Pi_{i-1} \right] \Pi_n(\rho_n, \rho_{MS})$$

- $|\mathcal{M}_0|^2 d\phi_0$: Born-level ME and phase space.
- F_i : PDF's from both sides for the *i*-parton state.
- $P_i(\rho, z) d\rho dz \approx \frac{|\mathcal{M}_i|^2 d\phi_i}{|\mathcal{M}_{i-1}|^2 d\phi_{i-1}} \equiv P_i^{ME}(z) d\rho dz$
- ρ, z: Splitting variables. Assume ρ is a suitable jet scale.
- ρ_{MS} : jet resolution scale.
- $\Pi_i(\rho_{i-1}, \rho_i)$: No-emission probabilities.

Exclusive jet cross sections No-emission probabilities Unitarity

No-emission probabilities (Sudakov form factors)

$$\Pi_{i}(\rho_{i},\rho_{i+1}) = \exp\left(-\int_{\rho_{i+1}}^{\rho_{i}} d\rho dz \,\alpha_{S} \frac{F_{i+1}}{F_{i}} P_{i+1}\right)$$

The probability of not having any splittings above the scale ρ_{i+1} starting the shower from the state *i* at scale ρ_i .

This is what generates the (N)LL resummation.

Introduction

Introduction [^]No-emission probabilities vel matching Unitarity .O Matching, The Basic Idea

Fixed-order expansion of a parton shower

$$(\text{using } \mathcal{P}_{i} = \frac{F_{i}}{F_{i-1}}P_{i})$$

$$\frac{d\sigma_{0}^{ex}}{d\phi_{0}} = F_{0} |\mathcal{M}_{0}|^{2} \left[1 - \alpha_{S} \int_{\rho_{MS}}^{\rho_{0}} d\rho dz \mathcal{P}_{1} + \frac{\alpha_{S}^{2}}{2} \left(\int_{\rho_{MS}}^{\rho_{0}} d\rho dz \mathcal{P}_{1}\right)^{2}\right]$$

$$\frac{d\sigma_{1}^{ex}}{d\phi_{0}} = F_{0} |\mathcal{M}_{0}|^{2} \alpha_{S} \mathcal{P}_{1} d\rho_{1} dz_{1}$$

$$\times \left[1 - \alpha_{S} \int_{\rho_{1}}^{\rho_{0}} d\rho dz \mathcal{P}_{1} - \alpha_{S} \int_{\rho_{MS}}^{\rho_{1}} d\rho dz \mathcal{P}_{2}\right]$$

$$\frac{d\sigma_{2}}{d\phi_{0}} = F_{0} |\mathcal{M}_{0}|^{2} \alpha_{S}^{2} \mathcal{P}_{1} d\rho_{1} dz_{1} \mathcal{P}_{2} d\rho_{2} dz_{2} \Theta(\rho_{1} - \rho_{2})$$

Unitary to all orders in α_s — total cross section is $F_0 |\mathcal{M}_0|^2$ 1-jet cross section will not even be correct to LO.

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Introduction	[^] No-emission probabilities
	Unitarity
	The Basic Idea

"Maeh, all event generators do is to squirt reasonably distributed mixture of particles in our detector simulation programs to understand our detector, and give a reasonable feeling for systematical errors on QCD predictions due to hadronization"

But what if we can systematically improve event generators to give predictions with formally controllable precision?



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ME reweighting

We really want to improve our parton shower.

The easiest thing is

$$P_i
ightarrow P_i^{ME} \equiv rac{\left|\mathcal{M}_i
ight|^2 d\phi_i}{\left|\mathcal{M}_{i-1}
ight|^2 d\phi_{i-1} d
ho dz}$$

This has been around quite a while in PYTHIA for the first splitting in some processes. Preserves the unitarity of the shower

Introduction	[^] No-emission probabilities
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$$\begin{aligned} \frac{d\sigma_0^{ex}}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \left[1 - \alpha_S \int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1^{ME} + \frac{\alpha_S^2}{2} \left(\int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1^{ME} \right)^2 \right] \\ \frac{d\sigma_1^{ex}}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S \mathcal{P}_1^{ME} d\rho_1 dz_1 \\ & \times \left[1 - \alpha_S \int_{\rho_1}^{\rho_0} d\rho dz \, \mathcal{P}_1^{ME} - \alpha_S \int_{\rho_{MS}}^{\rho_1} d\rho dz \, \mathcal{P}_2 \right] \\ \frac{d\sigma_2}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2 d\rho_2 dz_2 \Theta(\rho_1 - \rho_2) \end{aligned}$$

Still unitary to all orders of α_{S} . We can decease ρ_{MS} to the non-perturbative boundary ρ_{cut} .

Going to higher multiplicities turns out to be difficult.

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Matching: The Basic Idea

A fixed-order ME-generator gives the first few orders in $\alpha_{\rm s}$ exactly.

The parton shower gives approximate (N)LL terms to all orders in α_s through the Sudakov form factors.

- Take a parton shower and correct the first few terms in the resummation with (N)LO ME.
- Take events generated with (N)LO ME with subtracted Parton Shower terms. Add parton shower.
- Take events samples generated with (N)LO ME, reweight and combine with Parton showers:

Tree-level Merging

Has been around the whole millennium: CKKW(-L), MLM, ...

Combines samples of tree-level (LO) ME-generated events for different jet multiplicities. Reweight with proper Sudakov form factors (or approximations thereof).

Needs a merging scales to separate ME and shower region and avoid double counting. Only observables involving jets above that scale will be correct to LO.

Typically the merging scale dependence is beyond the precision of the shower: $\sim O(L^3 \alpha_s^2) \frac{1}{N^2} + O(L^2 \alpha_s^2)$.

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CKKW(-L)

Generate inclusive few-jet samples according to exact tree-level $|\mathcal{M}_n|^2$ using some merging scale $\rho_{\rm MS}$.

These are then made exclusive by reweighting no-emission probabilities (in CKKW-L generated by the shower itself)

Add normal shower emissions below $\rho_{\rm MS}$.

Add all samples together.

- Dependence on the merging scale cancels to the precision of the shower.
- If the merging scale is not defined in terms of the shower ordering variable, we need vetoed and truncated showers.
- Breaks the unitarity of the shower.

Tree-level matching

Tree-level Merging CKKW(-L)

Multi-jet tree-level matching

$$\begin{aligned} \frac{d\sigma_0^{ex}}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \left[1 - \alpha_S \int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1 + \frac{\alpha_S^2}{2} \left(\int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1 \right)^2 \right] \\ \frac{d\sigma_1^{ex}}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S \mathcal{P}_1^{ME} d\rho_1 dz_1 \\ & \times \left[1 - \alpha_S \int_{\rho_1}^{\rho_0} d\rho dz \, \mathcal{P}_1 - \alpha_S \int_{\rho_{MS}}^{\rho_1} d\rho dz \, \mathcal{P}_2 \right] \\ \frac{d\sigma_2}{d\phi_0} &= F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2^{ME} d\rho_2 dz_2 \Theta(\rho_1 - \rho_2) \end{aligned}$$

NOT unitary. Gives artificial dependence of ρ_{MS} . e.g. extra contribution to $\int \alpha_S \mathcal{P}_1^{ME}$ is $\sim \alpha_S^2 L^3$.

iN

Mature procedure. Available in HERWIG++, SHERPA, PYTHIA8.

The MLM-procedure (ALPGEN + HERWIG/PYTHIA) is similar, but even less control over the perturbative expansion.

There are recent procedures to restore unitarity:

- ► Vincia exponentiates the full *n*-parton matrix elements.
- UMEPS uses a add/subtract procedure combined with a re-clustering algorithm.



Tree-level matching NLO Matching

Tree-level Merging CKKW(-L)

UMEPS – Restoring unitarity

$$\frac{d\sigma_{0}^{ex}}{d\phi_{0}} = F_{0} \left| \mathcal{M}_{0} \right|^{2} \left[1 - \alpha_{S} \int_{\rho_{MS}}^{\rho_{0}} d\rho dz \, \mathcal{P}_{1} + \frac{\alpha_{S}^{2}}{2} \left(\int_{\rho_{MS}}^{\rho_{0}} d\rho dz \, \mathcal{P}_{1} \right)^{2} \right]$$

$$\frac{d\sigma_{1}^{ex}}{d\phi_{0}} = F_{0} \left| \mathcal{M}_{0} \right|^{2} \alpha_{S} \mathcal{P}_{1}^{ME} d\rho_{1} dz_{1} \left[1 - \alpha_{S} \int_{\rho_{1}}^{\rho_{0}} d\rho dz \, \mathcal{P}_{1} - \alpha_{S} \int_{\rho_{MS}}^{\rho_{1}} d\rho dz \, \mathcal{P}_{2} \right]$$

$$\frac{d\sigma_2}{d\phi_0} = F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2^{ME} d\rho_2 dz_2 \Theta(\rho_1 - \rho_2)$$

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* SIC

Tree-level matching NLO Matching Tree-level Merging CKKW(-L)

UMEPS – Restoring unitarity

$$\frac{d\sigma_0^{fx}}{d\phi_0} = F_0 \left| \mathcal{M}_0 \right|^2 \left[1 - \alpha_S \int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1 + \frac{\alpha_S^2}{2} \left(\int_{\rho_{MS}}^{\rho_0} d\rho dz \, \mathcal{P}_1 \right)^2 \right]$$

$$\frac{d\sigma_{1}^{fx}}{d\phi_{0}} = F_{0} \left| \mathcal{M}_{0} \right|^{2} \alpha_{S} \mathcal{P}_{1}^{ME} d\rho_{1} dz_{1} \left[1 - \alpha_{S} \int_{\rho_{1}}^{\rho_{0}} d\rho dz \, \mathcal{P}_{1} - \alpha_{S} \int_{\rho_{MS}}^{\rho_{1}} d\rho dz \, \mathcal{P}_{2} \right]$$

$$\frac{d\sigma_2}{d\phi_0} = F_0 \left| \mathcal{M}_0 \right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2^{ME} d\rho_2 dz_2 \Theta(\rho_1 - \rho_2)$$

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UMEPS – Restoring unitarity

$$\begin{aligned} \frac{d\sigma_{0}^{fx}}{d\phi_{0}} &= F_{0} \left| \mathcal{M}_{0} \right|^{2} \left[1 - \alpha_{S} \int_{\rho_{MS}}^{\rho_{0}} d\rho dz \,\mathcal{P}_{1} + \frac{\alpha_{S}^{2}}{2} \left(\int_{\rho_{MS}}^{\rho_{0}} d\rho dz \,\mathcal{P}_{1} \right)^{2} \right] \\ &- \int d\rho_{1} dz_{1} \frac{d\sigma_{1}^{fx}}{d\phi_{0} d\rho_{1} dz_{1}} \\ \frac{d\sigma_{1}^{fx}}{d\phi_{0}} &= F_{0} \left| \mathcal{M}_{0} \right|^{2} \alpha_{S} \mathcal{P}_{1}^{ME} d\rho_{1} dz_{1} \left[1 - \alpha_{S} \int_{\rho_{1}}^{\rho_{0}} d\rho dz \,\mathcal{P}_{1} - \alpha_{S} \int_{\rho_{MS}}^{\rho_{1}} d\rho dz \,\mathcal{P}_{2} \right] \\ &- \int d\rho_{2} dz_{2} \frac{d\sigma_{2}^{fx}}{d\phi_{0} d\rho_{1} dz_{1} d\rho_{2} dz_{2}} \\ \frac{d\sigma_{2}}{d\phi_{0}} &= F_{0} \left| \mathcal{M}_{0} \right|^{2} \alpha_{S}^{2} \mathcal{P}_{1}^{ME} d\rho_{1} dz_{1} \mathcal{P}_{2}^{ME} d\rho_{2} dz_{2} \Theta(\rho_{1} - \rho_{2}) \end{aligned}$$

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(a)

In CCKW we need to recreate the sequence of emissions.

In CKKW-L this is done by selecting a full parton shower history of an *n*-parton state.

In UMEPS performing the integration is simply to take the state where we have one jet less in the history.



But why worry about unitarity, the cross sections are never better than LO anyway, so scale uncertainties are huge.

CKKW(-L)

Tree-level matching



NLO

The anatomy of NLO calculations.

$$\langle \mathcal{O} \rangle = \int d\phi_n (B_n + V_n) \mathcal{O}_n(\phi_n) + \int d\phi_{n+1} B_{n+1} \mathcal{O}_{n+1}(\phi_{n+1}).$$

Not practical, since V_n and B_{n+1} are separately divergent, although their sum is finite.

The standard subtraction method:

$$\langle \mathcal{O} \rangle = \int d\phi_n \left(B_n + V_n + \sum_p \int d\psi_{n,p}^{(a)} S_{n,p}^{(a)} \right) \mathcal{O}_n(\phi_n)$$

$$+ \int d\phi_{n+1} \left(B_{n+1} \mathcal{O}_{n+1}(\phi_{n+1}) - \sum_p S_{n,p}^{(a)} \mathcal{O}_n(\frac{\phi_{n+1}}{\psi_{n,p}^{(a)}}) \right)$$

Tree-level matching NLO Basics NLO Matching MC@NLO Iulti-leg NLO Matching POWHEG

MC@NLO

(Frixione et al.)

The subtraction terms must contain all divergencies of the real-emission matrix element. A parton shower splitting kernel does exactly that.

Generating two samples, one according to $B_n + V_n + \int S_n^{PS}$, and one according to $B_{n+1} - S_n^{PS}$, and just add the parton shower from which S_n is calculated.

POWHEG

(Nason et al.)

Calculate $\overline{B}_n = B_n + V_n + \int B_{n+1}$ and generate *n*-parton states according to that.

Generate a first emission according to B_{n+1}/B_n , and then add any¹ parton shower for subsequent emissions.

¹As long as it is transverse-momentum ordered in the same way as in POWHEG or properly truncated



POWHEG and MC@NLO are very similar. They are both correct to NLO, but differ at higher orders

- POWHEG exponentiates also non singular pieces of the n+1 parton cross section
- ▶ POWHEG multiplies the n + 1 parton cross section with \overline{B}_n/B_n (the phase-space dependent *K*-factor).

POWHEG may also resum $k_{\perp} > \mu_R$, and will then generate additional logarithms, $log(S/\mu_R) \sim log(1/x)$.

Really NLO?

Do NLO-generators always give NLO-predictions?

POWHEG

Really NLO?

For simple Born-level processes such as Z^0 -production, all inclusive Z^0 observables will be correct to NLO.

- ► *Y*Z
- ► y_e
- ► p_{⊥e}

But note that for $p_{\perp e} > m_Z/2$ the prediction is only leading order!

Tree-level matching NLO Matching Multi-leg NLO Matching

Also $p_{\perp Z}$ is LO. To get NLO we need to start with Z+jet at Born-level and calculate full α_S^2 .

But for small $p_{\perp Z}$ the NLO cross section diverges due to $L^{2n}\alpha_s^n$, $L = \log(p_{\perp Z}/\mu_R)$.

If $L^2 \alpha_{\rm s} \sim$ 1, the $\alpha_{\rm s}^2$ corrections are parametrically as large as the NLO corrections.

Can be alleviated by clever choices for μ_{R} , but in general you need to resum.

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Assume we have a generator capable of doing three jets to NLO $(B_3 + V_3 + B_4)$

Really NLO?

Azimuth angle between the two hardest jets

NLO Matching



Multi-leg Matching

We need to be able to combine several NLO calculations and add (parton shower) resummation in order to get reliable predictions.

- No double (under) counting.
 - No parton shower emissions which are already included in (tree-level) ME states.
 - No terms in the PS no-emission resummation which are already in the NLO
- Dependence of any merging scale must not destroy NLO accuracy.
 - The NLO 0-jet cross section must not change too much when adding NLO 1-jet.
 - Dependence on logarithms of the merging scale should be less than L³α²_s in order for predictions to be stable for small scales.

SHERPA

First working solution for hadronic collisions.

CKKW-like combining of (MC@)NLO-generated events, fixing up double counting of NLO real and virtual terms.

Any jet multiplicity possible.

Dependence on merging scale canceled at NLO and parton-shower precision.

Residual dependence: $L^3 \alpha_s^2 / N_c^2$ — can't take merging scale too low.

MINLO

No merging scale!

- ► Take e.g. POWHEG Higgs+1-jet calculation down to very low p_⊥.
- Use clever (nodal) renormalization scales
- Multiply with (properly subtracted) Sudakov form factor
- Add non-leading terms to Sudakov form factor to get correct NLO 0-jet cross section.

Possible to go to NNLO!

Not clear how to go to higher jet multiplicities.

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UNLOPS

Start from UMEPS (unitary version of CKKW-L). Add (and subtract) *n*-jet NLO samples, fixing up double counting of NLO real and virtual terms.

$$\frac{d\sigma_1^{sub}}{d\phi_0} = \alpha_{\mathcal{S}} \mathcal{P}_1^{ME} d\rho_1 dz_1 \left[\Pi_0(\rho_0, \rho_1) - 1 + \alpha_{\mathcal{S}} \int_{\rho_1}^{\rho_0} d\rho dz \, \mathcal{P}_1 \right]$$

Note that PS uses $\alpha_S(\rho)$ and $f(x, \rho)$ rather than $\alpha_S(\mu_R)$ and $f(x, \mu_F)$



Any jet multiplicity possible.

Although there is a merging scale, the dependence of an *n*-jet cross section due to addition of higher multiplicities drops out completely. Merging scale can be taken arbitrarily small.

- Lots of negative weights.

Possible to go to NNLO? (See Stefan's talk)

Available in PYTHIA8 (and HERWIG++ in Simon's incarnation)

GENEVA

- Analytic (SCET) resummation of NLO cross section to NLL (or even NNLL!) in the merging scale variable.
- Only e^+e^- so far (W-production in *pp* on its way).

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Others

VINCIA

- Exponentiate NLO Matrix Elements in no-emission probability — no merging scale.
- ▶ Only e⁺e⁻ so far

FxFx

- MLM-like merging of different MC@NLO calculations
- Difficult to understand merging scale dependence

Multi-leg NLO Matching O

[^]UNLOPS Others

Les Houches comparison



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Open questions for (N)NLO

- Resummation scale and log(1/x)
- Phase space mapping mismatch
- Scale mismatch (vetoed and truncated showers)

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- How do we treat heavy quarks?
- Tuning

log(1/x)

Why not exponentiate the whole tree-level ME all the way up to the kinematical limit?

In the parton shower language, this is the no-emission probability – it should be there.

It will give $\log(S/\mu_R)^n \alpha_S^n$ terms which should be resummed.



Phase space mapping

What happens when the Parton Shower has different phase space mapping than what is used in the (N)NLO calculation. (Not MC@NLO).



Vetoed and truncated parton showers

Eg. when interfacing PYTHIA8 to POWHEG we have slightly different evolution variables.

Is this procedure good enough for (N)NLO matching?



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Vetoed and truncated parton showers

Eg. when interfacing PYTHIA8 to POWHEG we have slightly different evolution variables.

 \longrightarrow blackboard

Is this procedure good enough for (N)NLO matching?



Heavy quarks

Enter logs of m_b/μ_R , m_b/p_{\perp} , ...

It's not enough to generate $Wb\bar{b}$ to NLO to get a complete parton shower resummation. We typically need to combine:

W, Wj, Wb, Wjj, Wbj, Wbb, Wjjj, Wbjj, ...

Which flavour number scheme?

Generalized merging scale.

What about truncated showers?

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NLO Matching[^] Multi-leg NLO Matching Discussion

Tuning

Parton shower tunings typically boosts α_S to compensate for lack of ME-corrections. Matching needs new tunings.

Different tunings depending on number of merged multiplicities.

How do we treat MPI and UE?

References

(only arxiv numbers)

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- UMEPS: Lönnblad, 1211.4827
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- POWHEG: hep-ph/0409146
- SHERPA NLO matching: Höche, 1207.5030; Gehrmann, 1207.5031
- MINLO: Hamilton, 1212.4504
- UNLOPS: Lönnblad, 1211.7278 (Plätzer: 1211.5467)
- GENEVA: Aioli, 1211.7049
- VINCIA NLO: Hartgring, 1303.4974
- FxFx: Frederix, 1209.6215
- Les Houches comparison: Butterworth, 1405.1067



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3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use! Application rounds every 3 months.



MCnet projects Pythia Herwig Sherpa MadGraph Ariadne CEDAR



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- Eighth MCnet school in Lake District (UK)
 - Introduction to MCs
 - ME matching/merging
 - BSM simulation
 - Hands-on tutorials
 - etc
- August 24th-30th
- See

www.montecarlonet.org/Manchester2014

Application deadline June 10th!



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