Matching the Nagy-Soper parton shower at NLO

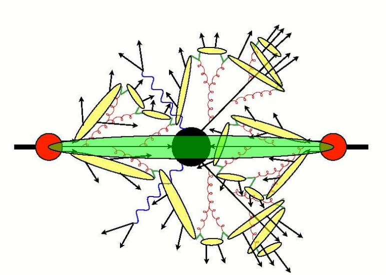
Heribertus Bayu Hartanto

with M. Czakon, M. Kraus and M. Worek

arXiv:1502.00925 [hep-ph]

PSR15 Krakow, May 27, 2015.

Monte Carlo Event Generator



http://www.hep.phy.cam.ac.uk/QCD_LHC/event.jpg

- Important tools to assist collider experiments
- Captures important aspects of high energy collisions, from hard scale to low scale
- Provides realistic description of final states
- Works very well to describe experimental data

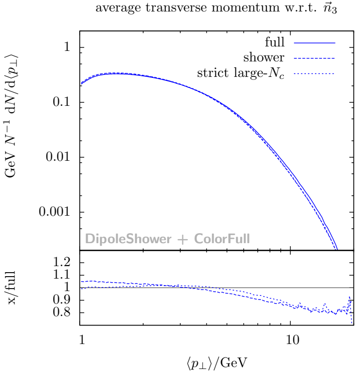
Improving theoretical prediction to reach better accuracy:

- Fixed order: (NLO, NNLO, N3LO) QCD, NLO EW $\rightarrow$ Tuesday's talk
- Matching parton shower to fixed order calculation $\rightarrow$ This morning's talk
- Merging matched calculation for different jet multiplicities (LO & NLO)

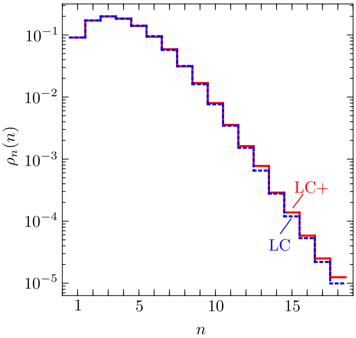
Parton showers in general have LC/LL accuracy

$\Rightarrow$ improvement on the parton shower front: inclusion of subleading effects

Subleading-Nc contributions in parton shower
unnoticeable in standard observables, visible for those sensitive to soft splitting



[Platzer, Sjodahl; arXiv:1201.0260]



[Nagy, Soper; arXiv:1501.00778]

Nagy-Soper construction: possibility to include subleading color & spin evolution

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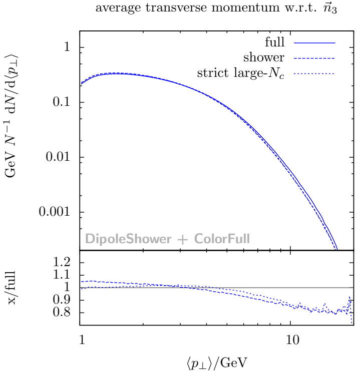

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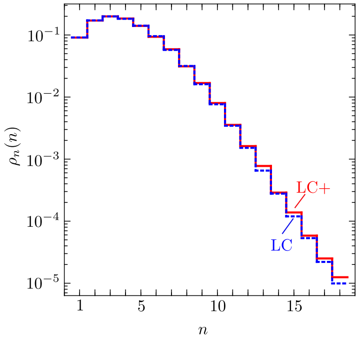


[Nagy, Soper; arXiv:1501.00778]

Nagy-Soper construction: possibility to include subleading color & spin evolution

This talk:

- Brief sketch of the Nagy-Soper parton shower
- Specify matching procedure between Nagy-Soper PS and NLO calculation
- Study a process within the matching scheme, i.e. $t\bar{t}j$ production at LHC

The Nagy-Soper Parton Shower

Nagy-Soper parton shower (1)

[Nagy, Soper; arXiv:0706.0017; arXiv:0801.1917; arXiv:0805.0216; arXiv:1202.4496]

Cross section for an observable F

$$\sigma[F] = \sum_m \frac{1}{m!} \int [d\{p,f\}_m] \langle \mathcal{M}(\{p,f\}_m) | F(\{p,f\}_m) | \mathcal{M}(\{p,f\}_m) \rangle \frac{f_a(\eta_a,\mu_F^2) f_b(\eta_b,\mu_F^2)}{4n_c(a)n_c(b) \times \text{flux}}$$

Quantum density matrix

$$\rho(\{p,f\}_m) \sim |\mathcal{M}(\{p,f\}_m)\rangle \langle \mathcal{M}(\{p,f\}_m)|$$

$|\mathcal{M}(\{p,f\}_m)\rangle$ is a vector in color $\otimes$ spin space

Perturbative evolution is described by a unitary operator $U(t_F, t_0)$, obeying

$$\frac{dU(t,t_0)}{dt} = [\mathcal{H}_I(t) - \mathcal{V}(t)] U(t,t_0)$$

- $\mathcal{H}_I(t)$: resolved emission, $\{p,f,s',c',s,c\}_m \to \{\hat{p},\hat{f},\hat{s}',\hat{c}',\hat{s},\hat{c}\}_{m+1}$
- $\mathcal{V}(t)$: unresolved/virtual emission, color configurations can change
  Can be decomposed into color diagonal and off-diagonal parts

$$\mathcal{V}(t) = \mathcal{V}_E(t) + \mathcal{V}_S(t)$$

Nagy-Soper parton shower (2)

More on $\mathcal{H}_I(t)$ (spin averaged version)

$$(\{\hat{p},\hat{f},\hat{c}',\hat{c}\}_{m+1}|\mathcal{H}_I(t)|\{p,f,c',c\}_m)$$

$$\begin{aligned}
&= (m+1)\sum_{l,k}\delta\big(t-\mathcal{T}_l(\{p,f\}_m)\big)\,(\{\hat{p},\hat{f}\}_{m+1}|\mathcal{P}_l|\{p,f\}_m) \\
&\times \frac{n_c(a)n_c(b)\eta_a\eta_b}{n_c(\hat{a})n_c(\hat{b})\hat{\eta}_a\hat{\eta}_b}\,\frac{f_{\hat{a}/A}(\hat{\eta}_a,\mu_F^2)f_{\hat{b}/B}(\hat{\eta}_b,\mu_F^2)}{f_{a/A}(\eta_a,\mu_F^2)f_{b/B}(\eta_b,\mu_F^2)} \\
&\times \frac{1}{2}\Big[\delta_{kl}(1-\delta_{\hat{f}_{m+1},g})\overline{w}_{ll}(\{\hat{p},\hat{f}\}_{m+1}) \\
&+\delta_{kl}\delta_{\hat{f}_{m+1},g}\Big[\overline{w}_{ll}(\{\hat{p},\hat{f}\}_{m+1})-\overline{w}_{ll}^{eikonal}(\{\hat{p},\hat{f}\}_{m+1})\Big] \\
&-(1-\delta_{kl})\delta_{\hat{f}_{m+1},g}A_{lk}(\{\hat{p}\}_{m+1})\overline{w}_{lk}^{dipole}(\{\hat{p},\hat{f}\}_{m+1})\Big] \\
&\times \Big[(\{\hat{c}',\hat{c}\}_{m+1}|T_l^\dagger(f_l\to\hat{f}_l+\hat{f}_{m+1})\otimes T_k(f_k\to\hat{f}_k+\hat{f}_{m+1})|\{c',c\}_m) \\
&\quad +(\{\hat{c}',\hat{c}\}_{m+1}|T_k^\dagger(f_k\to\hat{f}_k+\hat{f}_{m+1})\otimes T_l(f_l\to\hat{f}_l+\hat{f}_{m+1})|\{c',c\}_m)\Big]
\end{aligned}$$

$\rightarrow$ Every single choice leads to different shower evolution

Nagy-Soper parton shower (3)

Solution of evolution equation

$$U(t,t_0) = N(t,t_0) + \int_{t_0}^{t} d\tau\ U(t,\tau)\left[\mathcal{H}_I(\tau) - \mathcal{V}_S(\tau)\right] N(\tau,t_0)$$

Sudakov form factor

$$N(t,t_0) = \exp\left(-\int_{t_0}^{t} d\tau\ \mathcal{V}_E(\tau)\right)\ , \qquad \mathcal{V}(t) = \mathcal{V}_E(t) + \mathcal{V}_S(t)$$

- Exponentiation of $\mathcal{V}(t)$ can be cumbersome in the case of non-trivial color evolution [Platzer, Sjodahl; arXiv:1201.0260]
- Only the color diagonal part $\mathcal{V}_E(t)$ exponentiated
- Color off-diagonal part $\mathcal{V}_S(t)$ is treated perturbatively

Expectation value of observable F including shower effects

$$\sigma[F] = (F|\rho(t_F)) = (F|U(t_F,t_0)|\rho(t_0))$$

$t_F \rightarrow$ scale at which parton emission can not be described perturbatively

Nagy-Soper parton shower (4)

Features of Nagy-Soper parton shower:

- Splitting functions are different from Altarelli-Parisi
- Massive initial state charm and bottom quarks
- Constructed to include *full spin* evolution [Nagy, Soper; arXiv:0805.0216]
- $\cdots$ and *full color* evolution [Nagy, Soper; arXiv:1202.4496]
- Ordering variable Λ_l [Nagy, Soper; arXiv:1401.6366]

$$\Lambda_l^2 = \frac{|(\hat{p}_l \pm \hat{p}_{m+1})^2 - m_l^2|}{2p_l \cdot Q_0} Q_0^2, \qquad e^{-t} = \frac{\Lambda_l^2}{Q_0^2}$$

- PDFs are evolved according to shower splitting functions [Nagy, Soper; arXiv:1401.6368]

Public code: **DEDUCTOR** [Nagy, Soper; arXiv:1401.6364]
http://pages.uoregon.edu/soper/deductor/

- LC+ approximation [Nagy, Soper; arXiv:1202.4496]
- spin averaged evolution

Matching the Nagy-Soper shower at NLO

Matching fully inclusive processes

NLO density matrix

$$|\rho) = \underbrace{|\rho_m^{(0)})}_{\text{Born, } \mathcal{O}(1)} + \underbrace{|\rho_m^{(1)})}_{\text{Virtual, } \mathcal{O}(\alpha_s)} + \underbrace{|\rho_{m+1}^{(0)})}_{\text{Real, } \mathcal{O}(\alpha_s)} + \mathcal{O}(\alpha_s^2)$$

Shower evolution on the NLO density matrix

$$|\rho(t_F)) = U(t_F, t_0)|\rho) \approx |\rho) + \int_{t_0}^{t_F} d\tau \left[\mathcal{H}_I(\tau) - \mathcal{V}(\tau)\right] |\rho_m^{(0)}) + \mathcal{O}(\alpha_s^2)$$

Modify density matrix to remove double counting (MC@NLO approach)

[Frixione, Webber; hep-ph/0204244]

$$|\bar{\rho}) \equiv |\rho) - \int_{t_0}^{t_F} d\tau \left[\mathcal{H}_I(\tau) - \mathcal{V}(\tau)\right] |\rho_m^{(0)}) + \mathcal{O}(\alpha_s^2)$$

For an observable F, we have

$$\bar{\sigma}[F] = \frac{1}{m!} \int [d\Phi_m](F|U(t_F, t_0)|\Phi_m) \left[(\Phi_m|\rho_m^{(0)}) + (\Phi_m|\rho_m^{(1)}) + \int_{t_0}^{t_F} d\tau (\Phi_m|\mathcal{V}(\tau)|\rho_m^{(0)})\right]$$
$$+ \frac{1}{(m+1)!} \int [d\Phi_{m+1}](F|U(t_F, t_0)|\Phi_{m+1}) \left[(\Phi_{m+1}|\rho_{m+1}^{(0)}) - \int_{t_0}^{t_F} d\tau (\Phi_{m+1}|\mathcal{H}_I(\tau)|\rho_m^{(0)})\right]$$

Shower kernels are used to define subtraction terms of IR singularities, $t_F \to \infty$.
[Nagy, Soper; hep-ph/0503053; Hoeche, etal; arXiv:1111.1220]

$$\int_{t_0}^{\infty} d\tau \; \mathcal{H}_I(\tau) = \sum_I \mathbf{S}_I \int_0^{\infty} d\tau \; \delta(\tau - t_I)\Theta(\tau - t_0) = \sum_I \mathbf{S}_I \Theta(t_I - t_0)$$

$$\int_{t_0}^{\infty} d\tau \; \mathcal{V}(\tau) = \sum_I \int d\Gamma_I \; \mathbf{S}_I \Theta(t_I - t_0) \equiv \mathbf{I}(t_0) + \mathbf{K}(t_0)$$

Matched cross section including shower evolution is

$$\bar{\sigma}[F]^{PS} = \frac{1}{m!}\int [d\Phi_m](F|U(t_F, t_0)|\Phi_m)(\Phi_m|S) + \frac{1}{(m+1)!}\int [d\Phi_{m+1}](F|U(t_F, t_0)|\Phi_{m+1})(\Phi_{m+1}|H)$$

with

$$(\Phi_m|S) \equiv (\Phi_m|\rho_m^{(0)}) + (\Phi_m|\rho_m^{(1)}) + (\Phi_m|[\mathbf{I}(t_0) + \mathbf{K}(t_0) + \mathbf{P}]|\rho_m^{(0)})$$

$$(\Phi_{m+1}|H) \equiv (\Phi_{m+1}|\rho_{m+1}^{(0)}) - \sum_I (\Phi_{m+1}|\mathbf{S}_I|\rho_m^{(0)})\Theta(t_I - t_0)$$

Matching is a two step procedure: generation of the $(\Phi_m|S)$ and $(\Phi_{m+1}|H)$ samples followed by the application of $U(t_F, t_0)$.

Matching in the presence of singularity at LO

Inclusion of generation cuts

$$\bar{\sigma}[F]^{PS} = \frac{1}{m!}\int [d\Phi_m](F|U(t_F,t_0)|\Phi_m)(\Phi_m|S)F_I(\{\hat{p},\hat{f}\}_m) + \frac{1}{(m+1)!}\int [d\Phi_{m+1}](F|U(t_F,t_0)|\Phi_{m+1})(\Phi_{m+1}|H)F_I(\{p,f\}_{m+1})$$

Expanding the evolution operator

$$\bar{\sigma}[F]^{PS} \approx \frac{1}{m!}\int [d\Phi_m](F|\Phi_m)(\Phi_m|\left[|\rho_m^{(0)}) + |\rho_m^{(1)}) + \mathbf{P}|\rho_m^{(0)})\right] F_I(\{\hat{p},\hat{f}\}_m) + \frac{1}{(m+1)!}\int [d\Phi_{m+1}](F|\Phi_{m+1})(\Phi_{m+1}|\rho_{m+1}^{(0)})F_I(\{p,f\}_{m+1}) + \int \frac{[d\Phi_m]}{m!}\frac{[d\Phi_{m+1}]}{(m+1)!}\int_{t_0}^{t_F} d\tau\ (F|\Phi_{m+1})(\Phi_{m+1}|\mathcal{H}_I(\tau)|\Phi_m) \times(\Phi_m|\rho_m^{(0)})\left[F_I(\{\hat{p},\hat{f}\}_m) - F_I(\{p,f\}_{m+1})\right] + \mathcal{O}(\alpha_s^2)$$

Mismatch is cured by enforcing the subtraction terms to fulfil $F_I(\{\hat{p},\hat{f}\}_m)$

$$(\Phi_{m+1}|H) \to (\Phi_{m+1}|\tilde{H}) \equiv (\Phi_{m+1}|\rho^{(0)}_{m+1}) - \sum_l (\Phi_{m+1}|\mathbf{S}_l|\rho^{(0)}_m)\Theta(t_l - t_0) F_I(Q_l(\{p,f\}_{m+1}))$$

where $F_I(Q_l(\{p,f\}_{m+1})) = F_I(\{\hat{p},\hat{f}\}_m)$ and Q_l: inverse momentum mapping

With the modified $(\Phi_{m+1}|H)$,

$$\bar{\sigma}[F]^{PS} \approx \sigma^{NLO} + \int \frac{[d\Phi_m]}{m!}\frac{[d\Phi_{m+1}]}{(m+1)!}\int_{t_0}^{t_F} d\tau \; (F|\Phi_{m+1})(\Phi_{m+1}|\mathcal{H}_I(\tau)|\Phi_m)$$
$$\times(\Phi_m|\rho^{(0)}_m)\Big[1 - F_I(\{p,f\}_{m+1})\Big] F_I(\{\hat{p},\hat{f}\}_m) + \mathcal{O}(\alpha_s^2)$$

The double counting is removed if

$$\Big[1 - F_I(\{p,f\}_{m+1})\Big] F(\{p,f\}_{m+1}) = 0$$

This is achieved if $F_I(\{p,f\}_{m+1}) = 1$ for $F(\{p,f\}_{m+1}) \neq 0$

$\rightarrow$ generation cuts being more inclusive than the cuts on the final observable

Initial conditions for parton shower

The Nagy-Soper parton shower is ordered in the parameter Λ_l

$$e^{-t} = \frac{\Lambda_l^2}{Q_0^2}\,, \qquad \Lambda_l^2 = \frac{|(\hat{p}_l \pm \hat{p}_{m+1})^2 - m_l^2|}{2p_l \cdot Q_0} Q_0^2$$

- Initial time t_0 $\rightarrow$ has to be supplied by the user
- Choice of t_0 might influence distributions (e.g. $p_T(t\bar{t})$ in $pp \rightarrow t\bar{t} + X$) $\rightarrow$ need to provide sensible prescription
- In MC@NLO, PS contributions to the first emission are removed.

$$|\bar{\rho}) \equiv |\rho) - \int_{t_0}^{t_F} d\tau\, [\mathcal{H}_I(\tau) - \mathcal{V}(\tau)]\, |\rho_m^{(0)}) + \mathcal{O}(\alpha_s^2)$$

  Corrections to distributions affected by choices of t_0 are of $\mathcal{O}(\alpha_s^2)$ (although they can be large)
- We want the hardest spectrum to be described by the hard matrix element $\rightarrow$ allow splittings with virtualities lower that the ones already present in the hard matrix element.

Initial conditions for parton shower

Choose t_0 to approximate the virtuality on an event-by-event basis.

$$e^{-t_0} = \min_{i \neq j} \left\{ \frac{2p_i \cdot p_j}{Q_0^2} \right\} \tag{1}$$

For real radiation, use the subtraction terms to determine t_0 as follows

1. For each subtraction term $(\Phi_{m+1}|\mathbf{S}_l|\rho_m^{(0)})\Theta(t_l - t_0)F_I(Q_I(\{p,f\}_{m+1}))$ determine its individual t_0 according to (1), while t_l according to

$$e^{-t_l} = \frac{|(\hat{p}_l \pm \hat{p}_{m+1})^2 - m_l^2|}{2p_l \cdot Q_0} \tag{2}$$

   Retain t_l if $t_l > t_0$.

2. If there is at least one t_l, then evaluate t_0 according to

$$e^{-t_0} = \min_l \left(e^{-t_l} \right)$$

   where the minimum runs over all t_l found in the previous step.

3. Otherwise, apply (1) to the $(m+1)$-particle kinematics.

Summary of ambiguities

Parton masses

- Nagy-Soper parton shower treats bottom and charm quarks as massive. NLO calculation treats them as massless (bottom in 5FS).
- Need to introduce masses for the relevant quarks in the fixed order sample by performing an on-shell projection.

Parton distribution functions

- PDFs are evolved differently in the NLO calculation and in the shower

  NLO calculation: NLO PDFs are used

  Parton Shower: PDFs are evolved using Nagy-Soper splitting kernels
  The presence of quark masses
- The evolution is of higher order, NLO accuracy is maintained as long as the evolutions share a common point, e.g. at the low scale

Summary of ambiguities

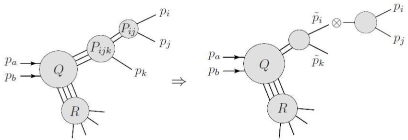
Initial shower time

- The choice of t_0 in the parton evolution is arbitrary
- Requirement: NLO prediction recovered for hard emissions
  Different choices of t_0 can achieve this, with either fixed or configuration dependent values.
- We pick one possible choice of t_0, but others are possible
- Vary t_0 to study the uncertainty of NLO+PS matching systematics.

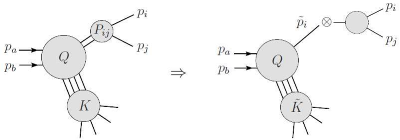
Implementation

Modifications in HELAC-DIPOLES

Implementation of Nagy-Soper subtraction scheme in HELAC-DIPOLES
[Bevilacqua, Czakon, Kubocz, Worek; arXiv:1308.5605]



Catani-Seymour



Nagy-Soper

- ✓ Easier dipole integration
- ✗ n^3 growth of subtraction terms

- ✗ More complex dipole integration
- ✓ n^2 growth of subtraction terms

Due to differences in splitting functions, momentum mappings, dipole phase space factorization.

Extensively tested for various processes
⇒ study of $pp \to b\bar{b}b\bar{b}$ [Bevilacqua, Czakon, Kramer, Kubocz, Worek; arXiv:1304.6860]

Modifications in HELAC-DIPOLES

Momentum mapping for initial state splitting

Implementation of subtraction scheme in HELAC-DIPOLES was based on the first Nagy-Soper parton shower paper [Nagy, Soper; arXiv:0706.0017]

DEDUCTOR uses revised momentum mapping for initial state splitting
$\Rightarrow$ improves log resummation for certain observables [Nagy, Soper; arXiv:0912.4534]
$\Rightarrow$ now implemented in HELAC-DIPOLES

Dynamical phase space restriction

$$\int_{t_0}^{\infty} d\tau \ \mathcal{H}_l(\tau) = \sum_l \mathbf{S}_l \Theta(t_l - t_0)$$

$$\int_{t_0}^{\infty} d\tau \ V(\tau) = \sum_l \int d\Gamma_l \ \mathbf{S}_l \Theta(t_l - t_0)$$

Effective cutoff on subtraction phase space

$\rightarrow$ similar to $\alpha_{\max}$ parameter in the Catani-Seymour scheme

Monte Carlo techniques

Event samples are generated using HELAC-1LOOP and HELAC-DIPOLES
Supply leading color and unpolarized events to DEDUCTOR

- Use reweighting for m-parton samples
  Generate unweighted LO events, then reweight according to

$$\omega_i(\{p,f\}_m) = 1 + \frac{(\{p,f\}_m|\rho_m^{(1)})}{(\{p,f\}_m|\rho_m^{(0)})} + \frac{(\{p,f\}_m|\mathbf{I}(t_0) + \mathbf{K}(t_0) + \mathbf{P}|\rho_m^{(0)})}{(\{p,f\}_m|\rho_m^{(0)})}$$

- Use unweighting for $(m+1)$-parton samples
- Pick the most probable diagonal color flow for each event
- Store the generated events in the LHE file format

Interface to DEDUCTOR

- Implement LHE file reader
- On-shell projection for charm and bottom quarks
- Translate color flow in the LHE file to DEDUCTOR's internal representation in terms of color strings

Application: $t\bar{t}j$ production at LHC

$pp \to t\bar{t}j$ at LHC

- NLO calculations available [Dittmaier, Uwer, Weinzierl '07; Melnikov, Schulze '10]
- NLO+PS using POWHEG method $\to$ available in POWHEG-BOX [Kardos, Papadopoulos, Trocsanyi '11; Alioli, Moch, Uwer '11]

Setup:

- $\sqrt{s} = 8$ TeV, $m_t = 173.5$ GeV, in PS: $m_b = 4.75$ GeV, $m_c = 1.4$ GeV
- MSTW2008NLO PDF sets, in PS: provided at $\mu_F = 1$ GeV
- $p_T^{\mathrm{gen}}(j) > 30$ GeV, $p_T(j) > 50$ GeV, $|y(j)| < 5$ GeV, anti-k_T with $\Delta R = 1$
- $\mu_R = \mu_F = m_t$
- LC and spin averaged shower evolution, full correlation in the subtraction
- Top decays, hadronization and multiple interactions are not included

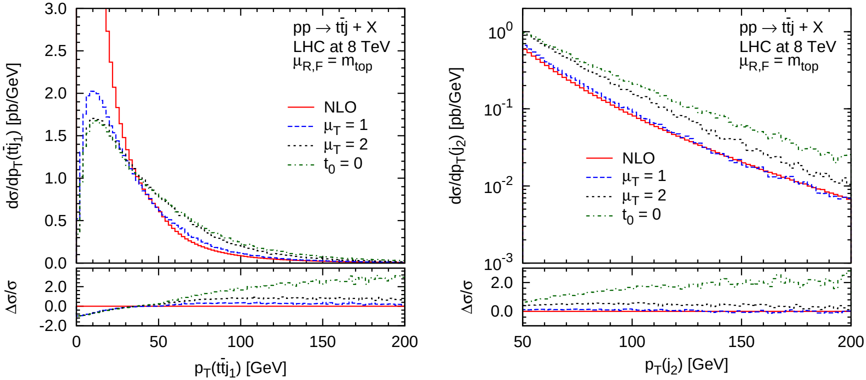
HELAC-NLO + DEDUCTOR v1.0.0 is compared to

- NLO calculation (from HELAC-1LOOP and HELAC-DIPOLES)
- aMC@NLO + (Pythia8 and Pythia6Q) (from MadGraph5_aMC@NLO)
- POWHEG + Pythia8 (from POWHEG-BOX)

Initial shower time, to a large extent, is arbitrary

μ_T: virtuality rescaling parameter

$$e^{-t_0} = \min_{i \neq j} \left\{ \frac{2p_i \cdot p_j}{\mu_T^2 Q_0^2} \right\}$$



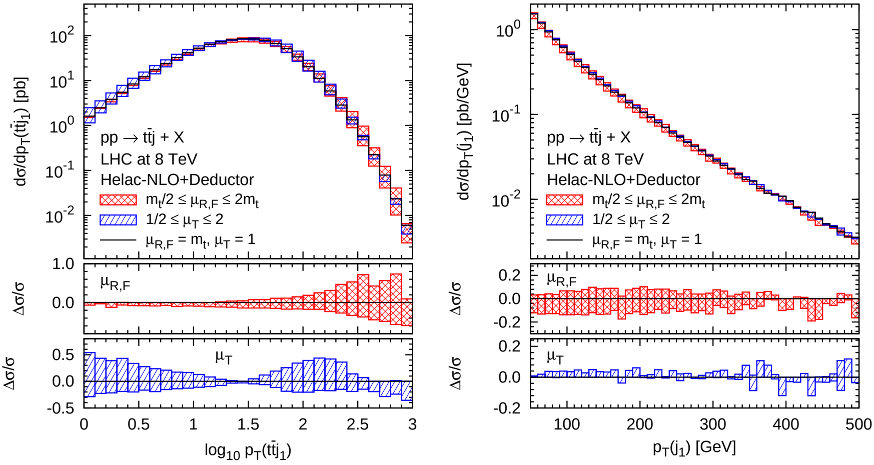
Higher μ_T value → larger correction in the high-p_T tail

To recover the NLO prediction, we set $\mu_{T_0} = 1$

Results and uncertainties

Scale uncertainties: $m_t/2 < \mu_{R,F} < 2m_t$

PS initial conditions: $1/2 < \mu_T < 2$



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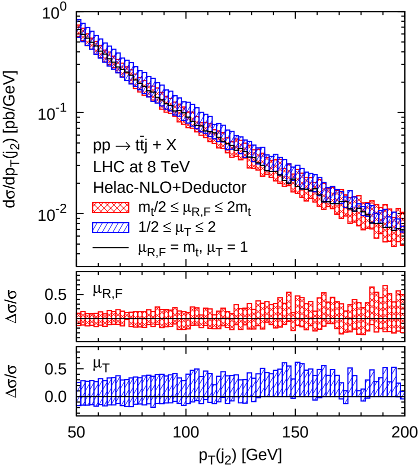
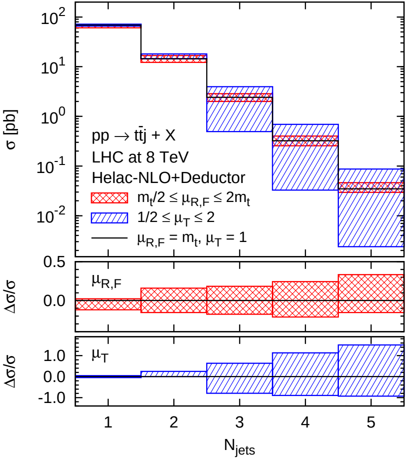
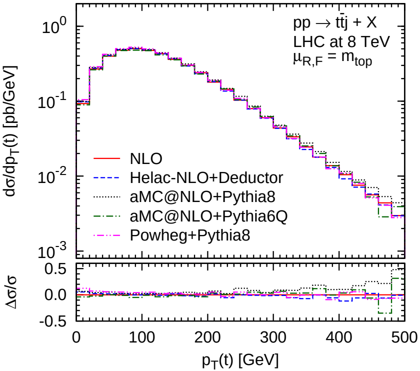
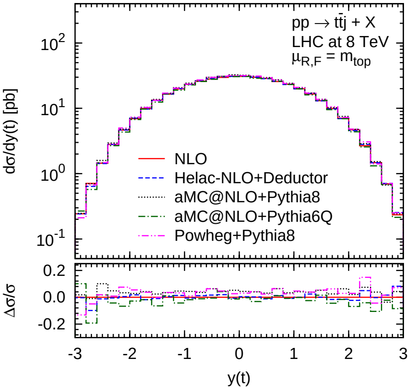




Comparison with other generators

Differences between: matching procedures and showers

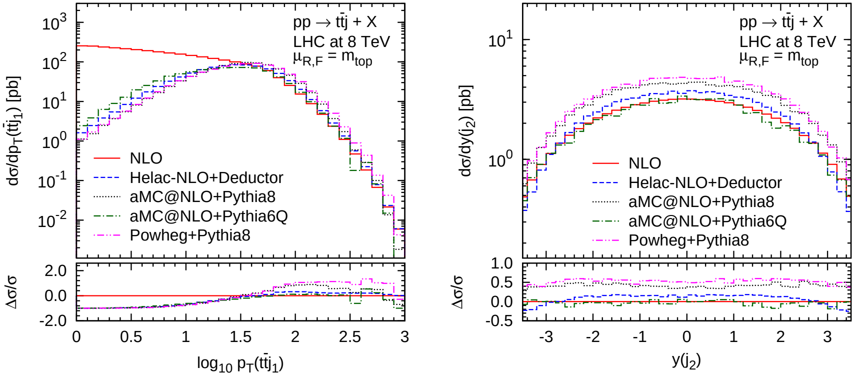




→ Agreement between different predictions for inclusive distributions

Comparison with other generators

Shower sensitive obervables



- Helac-NLO+Deductor preserves NLO spectrum (due to our choice of t_0)
- aMC@NLO+Pythia6Q recovers NLO results, produces softer emission
- Pythia8 (with MC@NLO and POWHEG matching) overshoots NLO prediction at high-p_T

Summary

Summary

- ✓ NLO matching scheme for the Nagy-Soper parton shower, based on the MC@NLO approach
- ✓ Implementation in HELAC-NLO framework → leading color and spin averaged
- ✓ Studied $t\bar{t}j$ production at the LHC using Helac-NLO+Deductor and performed comparison to other generators
- ✗ Resonance decays and nonperturbative effects need to be included
- ✗ Also full treatments of color and spin correlation in the matching implementation

Summary

- ✓ NLO matching scheme for the Nagy-Soper parton shower, based on the MC@NLO approach
- ✓ Implementation in HELAC-NLO framework → leading color and spin averaged
- ✓ Studied $t\bar{t}j$ production at the LHC using Helac-NLO+Deductor and performed comparison to other generators
- ✗ Resonance decays and nonperturbative effects need to be included
- ✗ Also full treatments of color and spin correlation in the matching implementation

THANK YOU!!!

BACKUPs

$pp \to t\bar{t}j + X$ total cross section

- NLO fixed order:

$$\sigma^{\rm NLO}_{pp\to t\bar{t}j+X} = 86.04\,^{+5.10\ (+6\%)}_{-11.41\ (-13\%)}\ \text{pb}$$

- NLO+PS from Helac-NLO matched to DEDUCTOR

$$\sigma^{\rm NLO+PS}_{pp\to t\bar{t}j+X} = 86.11\,^{+4.38\ (+5\%)}_{-10.88\ (-13\%)}\ [\text{scales}]\ ^{+0.80\ (+1\%)}_{+2.17\ (+3\%)}\ [\text{PS time}]\ \text{pb}$$

- NLO+PS from other generators

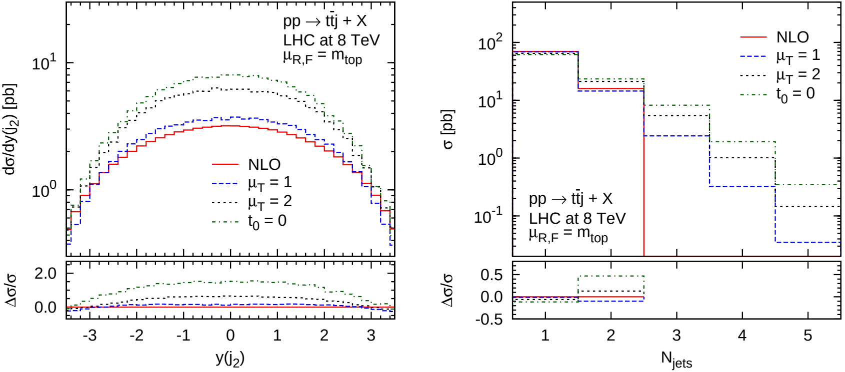
$$\sigma^{\rm NLO+PS}_{pp\to t\bar{t}j+X}(\text{aMC@NLO+Pythia6Q}) = 84.85\,^{+8.95\ (+11\%)}_{-13.75\ (-16\%)}\ [\text{scales}]\ \text{pb}$$
$$\sigma^{\rm NLO+PS}_{pp\to t\bar{t}j+X}(\text{aMC@NLO+Pythia8}) = 89.55\,^{+8.44\ (+9\%)}_{-15.41\ (-17\%)}\ [\text{scales}]\ \text{pb}$$
$$\sigma^{\rm NLO+PS}_{pp\to t\bar{t}j+X}(\text{POWHEG+Pythia8}) = 89.12\,^{+26.22\ (+29\%)}_{-8.96\ (-10\%)}\ [\text{scales}]\ \text{pb}$$

$pp \to t\bar{t}j + X$ total cross section

Generation cut dependence

p_T^{cut} [GeV]	$\sigma^{\mathrm{NLO+PS}}_{pp \to t\bar{t}j+X}$ [pb]	ϵ [‰]
5	86.51 ± 0.21	2.4
10	86.26 ± 0.17	2.0
15	86.22 ± 0.14	1.6
30	86.11 ± 0.13	1.5
40	86.01 ± 0.08	0.9
50	84.58 ± 0.07	0.8

$pp \to t\bar{t}j + X$: t_0 variation



$pp \to t\bar{t}j + X$: comparison with other generators