Precision calculation of top quark pair production in association with jets

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München, 11/08/2014

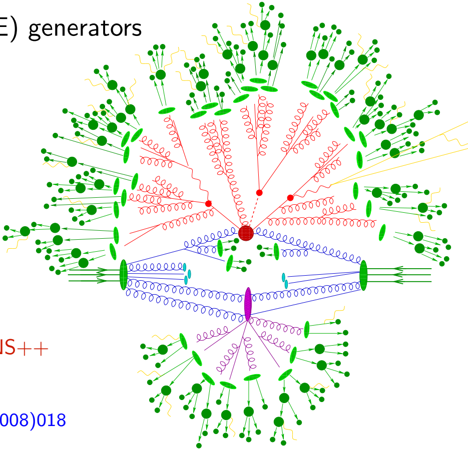
Phys.Rev. D88(2013)014040, arXiv:1402.6293*

*in coll. with S. Höche, J. Huang, F. Krauss, G. Luisoni, P. Maierhöfer, S. Pozzorini, F. Siegert, J. Winter

The SHERPA event generator framework

JHEP02(2009)007

- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
  COMIX JHEP12(2008)039, PRL109(2012)042001
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using
  YFS-resummation PHOTONS++ JHEP12(2008)018
- A minimum bias simulation SHRiMPS to appear



Sherpa's traditional strength is the perturbative part of the event

MEPS (CKKW), S-MC@NLO, MENLOPS, MEPS@NLO

Terminology

LoPs/NloPs matching

- combine LO/NLO description of a single process with parton shower
  → only this one process described to LO/NLO accuracy
  → subsequent multiplicities added at PS-accuracy
- multiple schemes, different ways to resolve overlap of competing descriptions
- examples: $pp \to h$, $pp \to W + j$, ...

Multijet merging

- combine multiple LoPs (→MePs)/NloPs (→MePs@Nlo) of subsequent multiplicity
  → resums emission scale hierarchies identical to parton shower wrt. the most inclusive process considered
  → corrects hard emission of jets to LO/NLO accuracy
- multiple schemes, different ways to resolve overlap of competing descriptions
- examples: $pp \to h$+jets, $pp \to t\bar{t}$+jets, ...

MEPS

Parton showers (operate in $N_c \to \infty$ limit):

$$\mathsf{PS}_n(t_c, t_{\mathsf{max}}) = \Delta_n(t_c, t_{\mathsf{max}}) + \int_{t_c}^{t_{\mathsf{max}}} \mathrm{d}t' \mathcal{K}_n(t')\, \Delta_n(t', t_{\mathsf{max}})$$

Multijet merging at leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\mathsf{MEPS}} = {} & \mathrm{d}\sigma_n^{\mathsf{LO}} \otimes \mathsf{PS}_n\, \Theta(Q_{\mathsf{cut}} - Q_{n+1}) \\ & + \mathrm{d}\sigma_{n+1}^{\mathsf{LO}}\, \Theta(Q_{n+1} - Q_{\mathsf{cut}})\, \Delta_n(t_{n+1}, t_n) \otimes \mathsf{PS}_{n+1}\, \Theta(Q_{\mathsf{cut}} - Q_{n+2}) \\ & + \mathrm{d}\sigma_{n+2}^{\mathsf{LO}}\, \Theta(Q_{n+2} - Q_{\mathsf{cut}})\, \Delta_n(t_{n+1}, t_n)\, \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \mathsf{PS}_{n+2}\end{aligned}$$

- restrict the parton shower on $2 \to n$ to emit only below Q_{cut}
- arbitrary jet measure $Q_n = Q_n(\Phi_n)$
- add the $n+1$ ME and its parton shower
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MePs

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MEPS

Parton showers (operate in $N_c \to \infty$ limit):

$$\text{PS}_n(t_c, t_\text{max}) = \Delta_n(t_c, t_\text{max}) + \int_{t_c}^{t_\text{max}} \mathrm{d}t' \mathcal{K}_n(t')\, \Delta_n(t',$$

Multijet merging at leading order:

$$\mathrm{d}\sigma^\text{MEPS} = \mathrm{d}\sigma_n^\text{LO} \otimes \text{PS}_n\, \Theta(Q_\text{cut} - Q_{n+1})$$
$$+\, \mathrm{d}\sigma_{n+1}^\text{LO}\, \Theta(Q_{n+1} - Q_\text{cut})\, \Delta_n(t_{n+1}, t_n) \otimes \text{PS}_{n+1}\, \Theta($$
$$+\, \mathrm{d}\sigma_{n+2}^\text{LO}\, \Theta(Q_{n+2} - Q_\text{cut})\, \Delta_n(t_{n+1}, t_n)\, \Delta_{n+1}(t_{n+2}, t$$

- restrict the parton shower on $2 \to n$ to emit only below Q_cu
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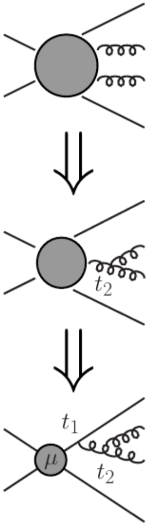
- add the $n+1$ ME and its parton shower
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

Scales:



$\alpha_s^{k+n}(\mu_\text{R}) = \alpha_s^k(\mu_\text{core})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$

MEPs

Parton showers (operate in $N_c \to \infty$ limit):

$$\mathsf{PS}_n(t_c, t_{\mathsf{max}}) = \Delta_n(t_c, t_{\mathsf{max}}) + \int_{t_c}^{t_{\mathsf{max}}} \mathrm{d}t' \mathcal{K}_n(t')\, \Delta_n(t', t_{\mathsf{max}})$$

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- restrict the parton shower on $2 \to n$ to emit only below Q_{cut}
- arbitrary jet measure $Q_n = Q_n(\Phi_n)$
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- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps Nason JHEP11(2004)040

MEPS@NLO

Parton showers for NLOPS (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathrm{PS}}_n(t_c, t_{\mathrm{max}}) = \tilde{\Delta}_n(t_c, t_{\mathrm{max}}) + \int_{t_c}^{t_{\mathrm{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\mathrm{max}})$$

Multijet merging at next-to-leading order:

$$\mathrm{d}\sigma^{\mathrm{MEPS@NLO}} = \mathrm{d}\sigma_n^{\mathrm{NLO}} \otimes \widetilde{\mathrm{PS}}_n\, \Theta(Q_{\mathrm{cut}} - Q_{n+1})$$

- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathrm{NLO}}$, iterate

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Multijet merging at next-to-leading order:

$$\begin{aligned}
\mathrm{d}\sigma^{\text{MEPS@NLO}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, &\Theta(Q_{\text{cut}} - Q_{n+1}) \\
&+ \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(Q_{n+1} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n) \right) \\
&\quad \otimes \widetilde{\text{PS}}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\
&+ \mathrm{d}\sigma_{n+2}^{\text{NLO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n) \right) \\
&\quad \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1}) \right) \otimes \widetilde{\text{PS}}_{n+2}
\end{aligned}$$

- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$, iterate

MePs@Nlo

Parton showers for NloPs (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathsf{PS}}_n(t_c, t_{\mathsf{max}}) = \tilde{\Delta}_n(t_c, t_{\mathsf{max}}) + \int_{t_c}^{t_{\mathsf{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\mathsf{max}})$$

Multijet merging at next-to-leading order:

$$\begin{aligned}
\mathrm{d}\sigma^{\text{MePs@Nlo}} = {} & \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - Q_{n+1}) \\
& + \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(Q_{n+1} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n) \right) \\
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& \qquad \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1}) \right) \otimes \widetilde{\mathsf{PS}}_{n+2}
\end{aligned}$$

- NloPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NloPs for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$, iterate

MePs@Nlo

Parton showers for NLOPs (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathsf{PS}}_n(t_c, t_{\mathsf{max}}) = \tilde{\Delta}_n(t_c, t_{\mathsf{max}}) + \int_{t_c}^{t_{\mathsf{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\mathsf{max}})$$

Multijet merging at next-to-leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\mathsf{MePs@Nlo}} = \mathrm{d}\sigma_n^{\mathsf{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - Q_{n+1}) \\ + \mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}\, \Theta(Q_{n+1} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ \otimes \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\mathsf{cut}} - Q_{n+2}) \\ + \mathrm{d}\sigma_{n+2}^{\mathsf{NLO}}\, \Theta(Q_{n+2} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\mathsf{PS}}_{n+2}\end{aligned}$$

- NLOPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPs for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}$ ... iterate

MePs@Nlo

Parton showers for NloPs (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathrm{PS}}_n(t_c, t_{\max}) = \tilde{\Delta}_n(t_c, t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\max})$$

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$$\begin{aligned}\mathrm{d}\sigma^{\text{MePs@Nlo}} &= \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\mathrm{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1}) \\ &\quad + \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(Q_{n+1} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ &\quad \otimes \widetilde{\mathrm{PS}}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\ &\quad + \mathrm{d}\sigma_{n+2}^{\text{NLO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ &\quad \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\mathrm{PS}}_{n+2}\end{aligned}$$

- NloPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NloPs for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$ iterate

MEPS@NLO

Parton showers for NLOPS (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathrm{PS}}_n(t_c, t_{\max}) = \tilde{\Delta}_n(t_c, t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
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$$\widetilde{\text{PS}}_n(t_c, t_{\text{max}}) = \tilde{\Delta}_n(t_c, t_{\text{max}}) + \int_{t_c}^{t_{\text{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\text{max}})$$

Multijet merging at next-to-leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\text{MEPS@NLO}} = &\,\mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1}) \\ &+ \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(Q_{n+1} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ &\quad \otimes \widetilde{\text{PS}}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\ &+ \mathrm{d}\sigma_{n+2}^{\text{NLO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ &\quad \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\text{PS}}_{n+2}\end{aligned}$$

- NLOPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPs for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$, iterate

MEPS@NLO

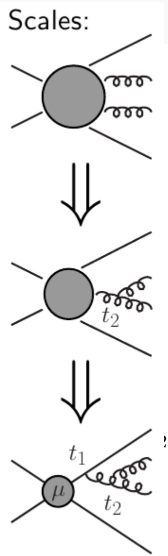
Parton showers for NLOPS (need to reproduce $N_c = 3$ singular li[...] .):

$$\widetilde{\mathsf{PS}}_n(t_c, t_{\mathsf{max}}) = \tilde{\Delta}_n(t_c, t_{\mathsf{max}}) + \int_{t_c}^{t_{\mathsf{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', \ldots$$

Multijet merging at next-to-leading order:

$$\mathrm{d}\sigma^{\mathsf{MEPS@NLO}} = \mathrm{d}\sigma_n^{\mathsf{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - Q_{n+1})$$
$$+ \mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}\, \Theta(Q_{n+1} - Q_{\mathsf{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)} \ldots$$
$$\otimes \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\mathsf{cut}} - Q_{n+2})$$
$$+ \mathrm{d}\sigma_{n+2}^{\mathsf{NLO}}\, \Theta(Q_{n+2} - Q_{\mathsf{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(\ldots$$
$$\times \Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n} \ldots$$

- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma[...]
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}$, itera[...]



$$\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\mathsf{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

MePs@Nlo

Parton showers for NLOPs (need to reproduce $N_c = 3$ singular li... .):

$$\widetilde{\mathrm{PS}}_n(t_c, t_{\max}) = \tilde{\Delta}_n(t_c, t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t'\, \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', $$

Multijet merging at next-to-leading order:

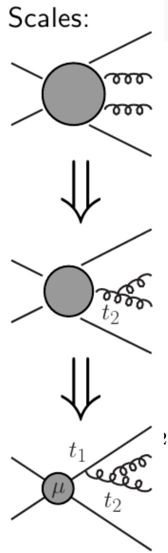
$$\mathrm{d}\sigma^{\text{MEPS@NLO}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\mathrm{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1})$$

$$+ \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(Q_{n+1} - Q_{\text{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}$$

$$\otimes \widetilde{\mathrm{PS}}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2})$$

$$+ \mathrm{d}\sigma_{n+2}^{\text{NLO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}($$

$$\times \Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_n$$



- NLOPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPs for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma...
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MeNloPs

$$
\begin{aligned}
\mathrm{d}\sigma^{\text{MeNloPs}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, &\Theta(Q_{\text{cut}} - Q_{n+1}) \\
&+ k_n(\Phi_{n+1})\, \mathrm{d}\sigma_{n+1}^{\text{LO}}\, \Theta(Q_{n+1} - Q_{\text{cut}})\, \Delta_n(t_{n+1}, t_n) \\
&\quad \otimes \text{PS}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\
&+ k_n(\Phi_{n+1}(\Phi_{n+2}))\, \mathrm{d}\sigma_{n+2}^{\text{LO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \\
&\quad \times \Delta_n(t_{n+1}, t_n)\, \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \text{PS}_{n+2}
\end{aligned}
$$

- restrict Mc@Nlo expression to region $Q < Q_{\text{cut}}$
- add in real radiation explicitly, as in MePs
- restore logarithmic behaviour by explicit Sudakov
- local K-factor for continuity at Q_{cut}

$$
k_n(\Phi_{n+1}) = \frac{\bar{\mathrm{B}}_n(\Phi_n(\Phi_{n+1}))}{\mathrm{B}_n(\Phi_n(\Phi_{n+1}))}\left(1 - \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}\right) + \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}
$$

- iterate

MeNloPs

$$\mathrm{d}\sigma^{\text{MeNloPs}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1})$$
$$+ k_n(\Phi_{n+1})\,\mathrm{d}\sigma_{n+1}^{\text{LO}}\,\Theta(Q_{n+1} - Q_{\text{cut}})\,\Delta_n(t_{n+1}, t_n)$$
$$\otimes \text{PS}_{n+1}\,\Theta(Q_{\text{cut}} - Q_{n+2})$$
$$+ k_n(\Phi_{n+1}(\Phi_{n+2}))\,\mathrm{d}\sigma_{n+2}^{\text{LO}}\,\Theta(Q_{n+2} - Q_{\text{cut}})$$
$$\times \Delta_n(t_{n+1}, t_n)\,\Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \text{PS}_{n+2}$$

- restrict Mc@Nlo expression to region $Q < Q_{\text{cut}}$
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- iterate

MENLOPS

$$\mathrm{d}\sigma^{\text{MENLOPS}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n \, \Theta(Q_{\text{cut}} - Q_{n+1})$$
$$+ k_n(\Phi_{n+1}) \, \mathrm{d}\sigma_{n+1}^{\text{LO}} \, \Theta(Q_{n+1} - Q_{\text{cut}}) \, \Delta_n(t_{n+1}, t_n)$$
$$\otimes \text{PS}_{n+1} \, \Theta(Q_{\text{cut}} - Q_{n+2})$$
$$+ k_n(\Phi_{n+1}(\Phi_{n+2})) \, \mathrm{d}\sigma_{n+2}^{\text{LO}} \, \Theta(Q_{n+2} - Q_{\text{cut}})$$
$$\times \Delta_n(t_{n+1}, t_n) \, \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \text{PS}_{n+2}$$

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- iterate

MENLOPS

$$
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\mathrm{d}\sigma^{\text{MENLOPS}} = {}& \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1}) \\
&+ k_n(\Phi_{n+1})\, \mathrm{d}\sigma_{n+1}^{\text{LO}}\, \Theta(Q_{n+1} - Q_{\text{cut}})\, \Delta_n(t_{n+1}, t_n) \\
&\quad \otimes \text{PS}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\
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$$

- iterate

MENLOPS

$$\mathrm{d}\sigma^{\textsf{MENLOPS}} = \mathrm{d}\sigma_n^{\textsf{NLO}} \otimes \widetilde{\textsf{PS}}_n\, \Theta(Q_{\textsf{cut}} - Q_{n+1})$$
$$+\, k_n(\Phi_{n+1})\, \mathrm{d}\sigma_{n+1}^{\textsf{LO}}\, \Theta(Q_{n+1} - Q_{\textsf{cut}})\, \Delta_n(t_{n+1}, t_n)$$
$$\otimes\, \textsf{PS}_{n+1}\, \Theta(Q_{\textsf{cut}} - Q_{n+2})$$
$$+\, k_n(\Phi_{n+1}(\Phi_{n+2}))\, \mathrm{d}\sigma_{n+2}^{\textsf{LO}}\, \Theta(Q_{n+2} - Q_{\textsf{cut}})$$
$$\times\, \Delta_n(t_{n+1}, t_n)\, \Delta_{n+1}(t_{n+2}, t_{n+1})\, \otimes \textsf{PS}_{n+2}$$

- restrict MC@NLO expression to region $Q < Q_{\textsf{cut}}$
- add in real radiation explicitly, as in MEPS
- restore logarithmic behaviour by explicit Sudakov
- local K-factor for continuity at $Q_{\textsf{cut}}$

$$k_n(\Phi_{n+1}) = \frac{\bar{\mathrm{B}}_n\,(\Phi_n(\Phi_{n+1}))}{\mathrm{B}_n\,(\Phi_n(\Phi_{n+1}))}\left(1 - \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}\right) + \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}$$

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$$
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\mathrm{d}\sigma^{\text{MENLOPS}} = {} & \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n\, \Theta(Q_{\text{cut}} - Q_{n+1}) \\
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& \quad \otimes \text{PS}_{n+1}\, \Theta(Q_{\text{cut}} - Q_{n+2}) \\
& + k_n(\Phi_{n+1}(\Phi_{n+2}))\, \mathrm{d}\sigma_{n+2}^{\text{LO}}\, \Theta(Q_{n+2} - Q_{\text{cut}}) \\
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$$

- iterate

Scale choices

CKKW scales

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2)\,\alpha_s(t_1)\cdots\alpha_s(t_n) \qquad \mu_{F,a/b}^2 = t_{\text{ext},a/b} \qquad \mu_Q^2 = \mu_{\text{core}}^2$$

Free choices

1. μ_{core} – scale of core process identified through clustering with inverse parton shower
2. $\mu_{R/F}$ beyond 1-loop running
   - calculate with chosen $\mu_{R/F}$
   - include renormalisation and factorisation terms to shift the 1-loop running to above

$$\mathrm{B}_n\,\frac{\alpha_s(\mu_R)}{\pi}\,\beta_0\left(\log\frac{\mu_R}{\mu_{R,\text{CKKW}}}\right)^{n+k}$$

   and

$$\mathrm{B}_n\,\frac{\alpha_s}{2\pi}\,\log\frac{\mu_F}{t_{\text{ext}}}\sum_{c=q,g}\int_{x_a}^1\frac{\mathrm{d}z}{z}\,P_{ac}(z)f_c(x_a/z,\mu_F^2)$$

$\rightarrow$ same as in UNLOPS   Lönnblad, Prestel JHEP03(2013)166, Plätzer JHEP08(2013)114

Scale choices

CKKW scales

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2)\,\alpha_s(t_1)\cdots\alpha_s(t_n) \qquad \mu_{F,a/b}^2 = t_{\text{ext},a/b} \qquad \mu_Q^2 = \mu_{\text{core}}^2$$

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→ same as in UNLOPS   Lönnblad, Prestel JHEP03(2013)166, Plätzer JHEP08(2013)114

Recent results

Multijet merging at NLO accuracy (MEPS@NLO)

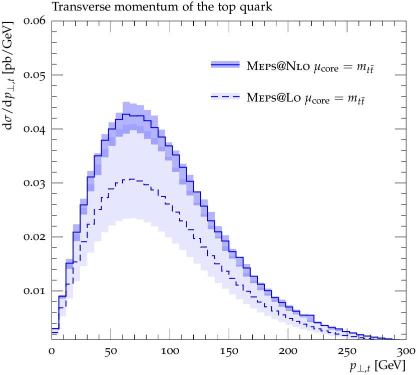
- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT
  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM/MCFM
  Höche, Krauss, MS, Siegert, contribution to YR3 arXiv:1307.1347
  Höche, Krauss, MS arXiv.1401.7971
  MS, Zapp, contribution to LH13 arXiv:1405.1067
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM/OPENLOOPS
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
  Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert arXiv:1402.6293
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert JHEP01(2014)046
- $pp \to VH +$ jets, $pp \to VV +$ jets, $pp \to VVV +$ jets
  – SHERPA+OPENLOOPS
  Höche, Krauss, Pozzorini, MS, Thompson, Zapp Phys.Rev.D89(2014)114006

Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} + $ jets – $\mathrm{A_{FB}}$

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GoSam
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV



- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$

  1) $\mu_{\text{core}} = m_{t\bar{t}}$

  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – A_{FB}

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

Setup: $p\bar{p} \to t\bar{t}+$ jets

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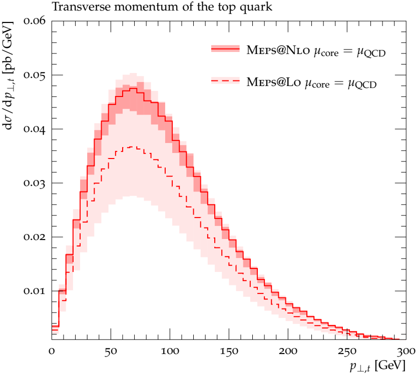

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Results – $p\bar{p} \to t\bar{t} + $jets – A_{FB}

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
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- virtual MEs from GoSam
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  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
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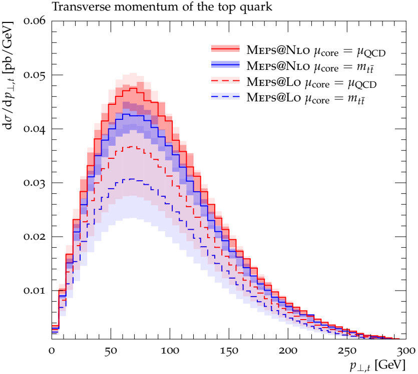
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV



- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$

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  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} +$ jets – A_{FB}

- Definition of forward-backward asymmetry of an observable $\mathcal{O}$

$$A_{\mathsf{FB}}(O) \;=\; \frac{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} - \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} + \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}$$

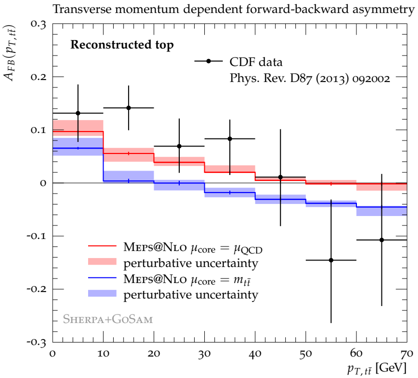
- A_{FB} is ratio of expectation values
  $\to$ conventional scale variations by factor 2 will largely cancel for uncertainty on A_{FB}

$\Rightarrow$ use different functional forms of the scale defintion that behave differently in $\Delta y > 0$ and $\Delta y < 0$ for a realistic estimate of uncertainty

Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – A_{FB}

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

CDF data Phys.Rev.D87(2013)092002



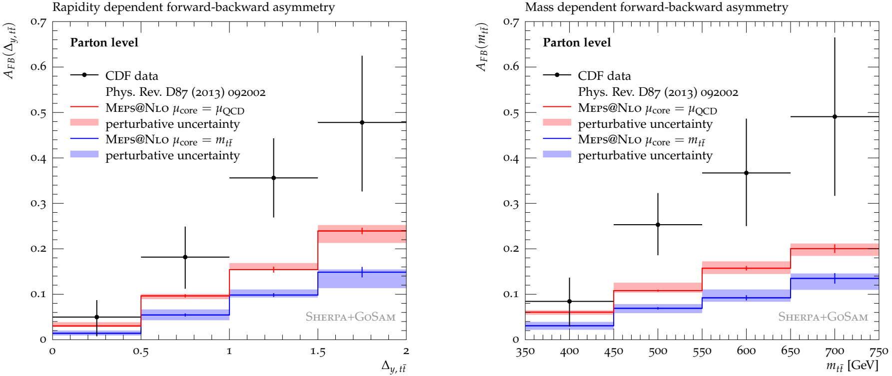
$p\bar{p} \to t\bar{t}$+jets (0,1 @ NLO)

- $A_{FB}(p_{\perp,t\bar{t}})$ NLO accurate in all but the first bin
- tops reconstructed from decay products (jets, lepton, MET)
- no EW corrections

Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – A_{FB}

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

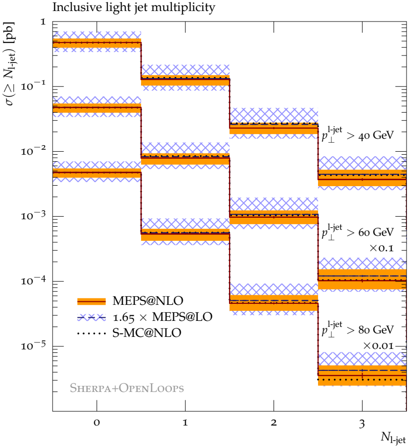
CDF data Phys.Rev.D87(2013)092002



- parton level (exact top quarks)
- no EW corrections ($\approx 20\%$) effected
- right qualitative bahviour, but consistently below data

Results – pp → $t\bar{t}$+jets

Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert in arXiv:1401.7971



$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

- scales:

  $\alpha_s^{2+n}(\mu_R) = \alpha_s^2(\mu_{\text{core}}) \prod_{i=1}^{n} \alpha_s(t_i)$,

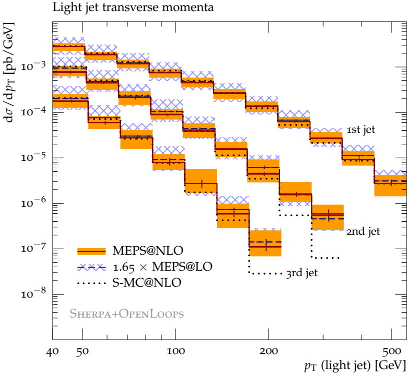
  $\mu_F = \mu_Q = \mu_{\text{core}}$ on $2 \to 2$

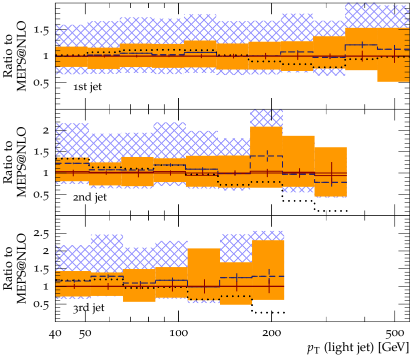
  $Q_{\text{cut}} = 30$ GeV

$$\mu_{\text{core}} = -\frac{2}{\frac{1}{p_0 p_1} + \frac{1}{p_0 p_2} + \frac{1}{p_0 p_3}}$$

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_Q^{\text{def}}$
- $Q_{\text{cut}} \in \{20, 30, 40\}$ GeV
- spin-correlated dileptonic decays at LO accuracy

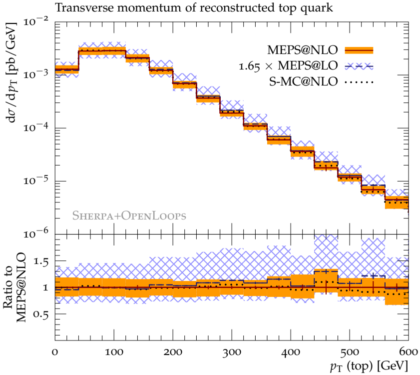
Results – pp → $t\bar{t}$+jets





- Shapes are stable
- Uncertainties are much smaller where higher accuracy is employed

Results – pp → $t\bar{t}$+jets

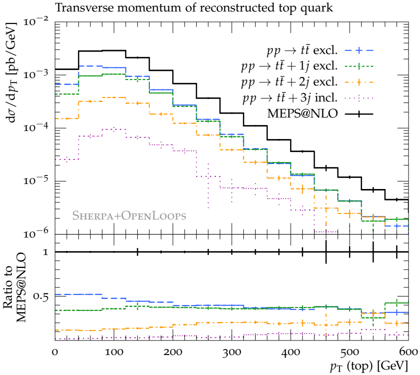


$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

Reconstructed top $p_\perp$

- again, shapes are stable
- noticable reduction in uncertainty
- inclusive observable, but large number of events with ≥1 jet necessitates mutlijet merging for best accuracy

Results – $pp \to t\bar{t}$+jets

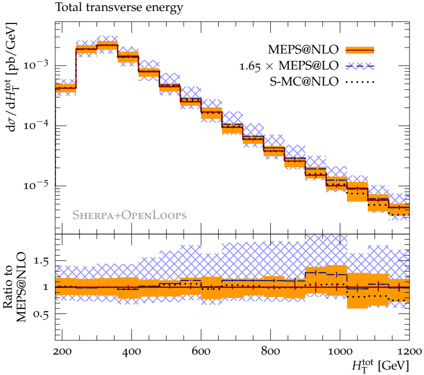


$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

Reconstructed top $p_\perp$

- again, shapes are stable
- noticable reduction in uncertainty
- inclusive observable, but large number of events with $\geq$1 jet necessitates mutlijet merging for best accuracy

Results – $\mathrm{pp} \to \mathrm{t\bar{t}}$+jets



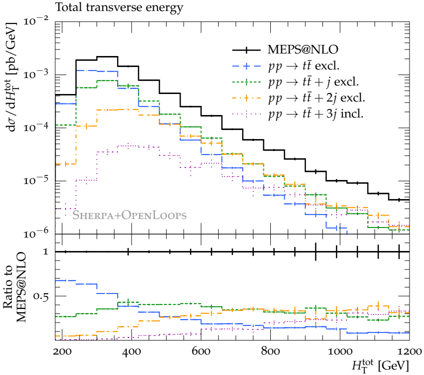
$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

Total transverse energy

$$H_T^{tot} = \sum_{\text{b-jets}} p_\perp + \sum_{\text{l-jets}} p_\perp + \sum_{\text{lep}} p_\perp + E_T^{miss}$$

- relevant observable for new physics searches
- slight correction to MEPS shapes at high H_T^{tot}
- noticable reduction in uncert., especially at high H_T^{tot}
- inclusive observable, but dominated by configurations with different number of jets at successively higher H_T^{tot}

Results – $\mathrm{pp} \to \mathrm{t\bar{t}}$+jets



$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

Total transverse energy

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Conclusions

MePs@Nlo

- multijet merging at NLO proceeds schematically as at LO
  $\rightarrow$ introduce MC-counterterm to retain NLO accuracy
- preserves NLO accuracy of the ME and accuracy of the PS in resumming hierarchies of emission scales
  $\rightarrow$ scale setting essential for recovering PS resummation
  $\rightarrow$ core scale and beyond 1-loop running can of course be chosen freely

Important applications in top-quark physics

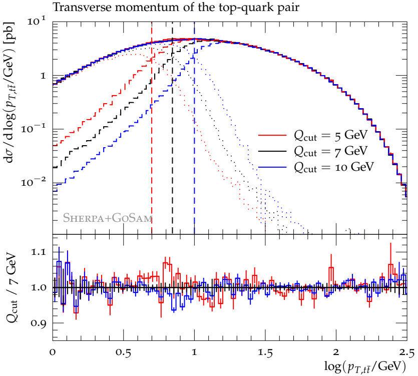
- A_{FB} intricate observable, simple fixed-order calculation does not do it justice, care must be take to evaluate uncertainties
- at the LHC $t\bar{t}$-production likely accompanied by many jets
  $\rightarrow$ need multijet merging to account for both fixed-order accuracy and resummation effects

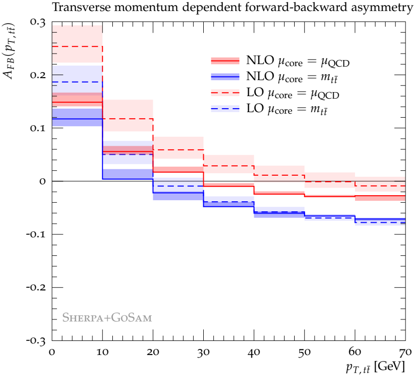
current release Sherpa-2.1.1

http://sherpa.hepforge.org

Thank you for your attention!

Results – $p\bar{p} \to t\bar{t} + \text{jets}$





- very small Q_{cut} dependence
- scale variation shrinks going LO to NLO (both factor and functional form)

Results – pp → $t\bar{t}$+jets