Reweighting QCD matrix-element and parton-shower calculations

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Introduction

Sources of systematic uncertainties of theory calculations can generally be grouped into the following categories

- *paramentric* input parameters, e.g. $\alpha_s(m_Z)$, masses, PDFs
- *perturbative* fixed and logarithmic order, large-N_c approx., etc.
- *algorithmic* choices in implementation, e.g. functional form of PS evolution kernels, recoil scheme, matching algorithm, merging method
- *non-perturbative* multiple interaction, hadronisation, etc.

Extracting them through rerunning not feasible due to increasing running time the more involved the calculation is and the shear number of input quantities ($\mathcal{O}$ (few100) variations to be calculated).

I will focus on parametric ($\alpha_s(m_Z)$, PDFs) and perturbative (μ_R, μ_F) uncertainties. Algorithmic dependences will not be covered here. Also, non-perturbative uncertainties are a whole different matter.

Fixed-order variations

- LO trivial

$$\langle O \rangle^{\text{LO}} = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, O(\Phi_B)$$

- NLO work in CS subtraction, independent of loop generator

- book-keep 18 weight components (2 VI, 16 KP)
  R and each D_S transform same as B

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$$\mathrm{B}(\Phi_B) \;=\; \alpha_s^n(\mu_R^2)\, f_a(x_a,\mu_F^2)\, f_b(x_b,\mu_F^2)\, \mathrm{B}'(\Phi_B)$$

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$$+ \int \mathrm{d}\Phi_R \left[\mathrm{R}(\Phi_R)\, O(\Phi_R) - \sum_j \mathrm{D}_{S,j}(\Phi_{B,j}\cdot\Phi_1^j)\, O(\Phi_{B,j})\right]$$

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$l_R = \log(\mu_R^2/\tilde{\mu}_{R,\mathrm{ref}}^2)$

$$\mathrm{VI}(\Phi_B) \;=\; \alpha_s^{n+1}(\mu_R^2)\, f_a(x_a,\mu_F^2)\, f_b(x_b,\mu_F^2)\, \left[\mathrm{VI}'(\Phi_B) + {c_R'}^{(0)} l_R + \tfrac{1}{2}\, {c_R'}^{(1)} l_R^2\right]$$

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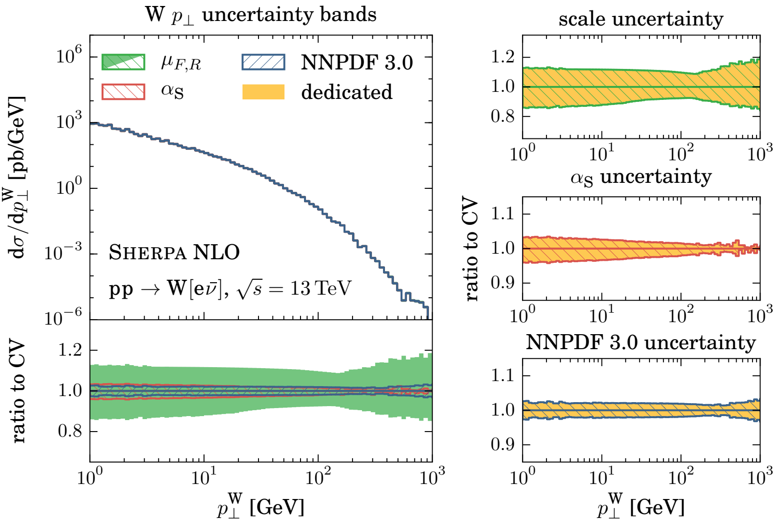
$$\begin{aligned}\mathrm{KP}(\Phi_B,x'_{a/b}) = \alpha_s^{n+1}(\mu_R^2)\Big[&\Big(f_a^q c_{F,a}'^{(0)} + f_a^q(x'_a)\, c_{F,a}'^{(1)} + f_a^g c_{F,a}'^{(2)} + f_a^g(x'_a)\, c_{F,a}'^{(3)}\Big) f_b(x_b,\mu_F^2)\\ &+ f_a(x_a,\mu_F^2)\Big(f_b^q c_{F,b}'^{(0)} + f_b^q(x'_b)\, c_{F,b}'^{(1)} + f_b^g c_{F,b}'^{(2)} + f_b^g(x'_b)\, c_{F,b}'^{(3)}\Big)\Big]\end{aligned}$$

$$c_{F,a/b}'^{(i)} = \tilde{c}_{F,a/b}^{(i)} + \bar{c}_{F,a/b}^{(i)}\, l_F$$

$l_F = \log(\mu_F^2/\tilde{\mu}_{F,\mathrm{ref}}^2)$

- book-keep 18 weight components (2 VI, 16 KP)
  R and each D_S transform same as B
  same as used in SHERPA NTUPLES

Closure tests: $pp \to W$ @ NLO



Parton shower variations

$$\langle O\rangle^{\text{LoPs}} = \int \text{d}\Phi_B\, \mathrm{B}(\Phi_B)\, \mathrm{PS}(O,\Phi_B;\mu_Q^2)$$

- as discussed in Johannes' talk, need to trace parameter dependence through veto algorithm

$$\mathrm{K}_n(t_2,t_1;k_{\alpha_s},k_f;\alpha_s,f) \;=\; \sum_{ij}\sum_{k}\; \alpha_s(k_{\alpha_s}t)\,\mathrm{K}'_{ij,k}(t,z)\,\frac{f_{c'}(\frac{\eta_c}{x},k_f t)}{f_c(\eta_c,k_f t)}$$

- splitting kernels linear in α_s and PDF ratio
- in the following consider variations of paramentric functions f and α_s, and scales k_{α_s} and k_f
- no variation of starting scale μ_Q^2 or emission scales t_i
- control number of reweighted emissions, n_{PS}

Parton shower variations

$$\mathrm{PS}(O,\Phi_n;t') = \Delta_n(t_{\mathrm{IR}},t')\,O(\Phi_n) + \int_{t_{\mathrm{IR}}}^{t'} \mathrm{d}\Phi_1\,\mathrm{K}_n(\Phi_1)\,\Delta_n(t,t')\,\mathrm{PS}(O,\Phi_{n+1};t)$$

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Parton shower variations

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Parton shower variations

$$\mathrm{K}_n(t_2, t_1; k_{\alpha_s}, k_f; \alpha_s, f) \;=\; \sum_{ij}\sum_{k}\; \alpha_s(k_{\alpha_s} t)\,\mathrm{K}'_{ij,k}(t,z)\,\frac{f_{c'}(\frac{\eta_c}{x}, k_f t)}{f_c(\eta_c, k_f t)}$$

- variation $\alpha_s \to \tilde{\alpha}_s$, $f \to \tilde{f}$, $k_{\alpha_s} \to \tilde{k}_{\alpha_s}$ and/or $k_f \to \tilde{k}_f$ gives
  $\to$ probability to accept $P_{\mathrm{acc}} = \frac{\mathrm{K}}{\hat{\mathrm{K}}} \to \tilde{P}_{\mathrm{acc}} = q_{\mathrm{acc}} P_{\mathrm{acc}}$

$$q_{\mathrm{acc}} \equiv \frac{\tilde{\alpha}_s(\tilde{k}_{\alpha_s} t)}{\alpha_s(k_{\alpha_s} t)}\;\frac{\tilde{f}_{c'}(\frac{\eta_c}{x}, \tilde{k}_f t)}{f_{c'}(\frac{\eta_c}{x}, k_f t)}\;\frac{f_c(\eta_c, k_f t)}{\tilde{f}_c(\eta_c, \tilde{k}_f t)}$$

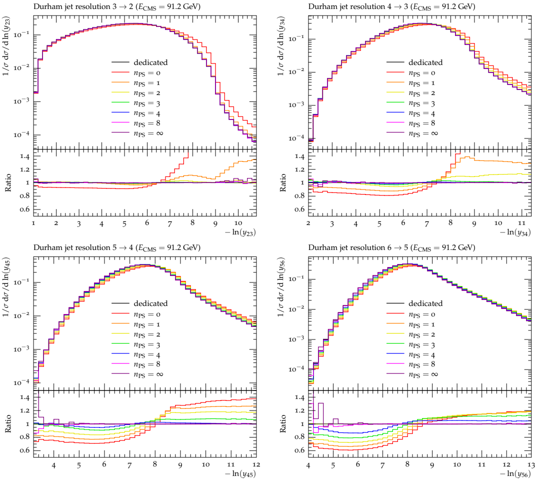
  $\to$ probability to reject $P_{\mathrm{rej}} \to \tilde{P}_{\mathrm{rej}} = q_{\mathrm{rej}} P_{\mathrm{rej}} = 1 - \tilde{P}_{\mathrm{acc}}$

$$q_{\mathrm{rej}} \equiv \left[1 + (1 - q_{\mathrm{acc}})\,\frac{P_{\mathrm{acc}}}{1 - P_{\mathrm{acc}}}\right]$$

  $\to$ numerical instability as $P_{\mathrm{acc}} \to 1$

Höche, Siegert, Schumann Phys.Rev.D81(2010)034026
Bellm et.al. arXiv:1605.08256
Mrenna, Skands arXiv:1605.08352

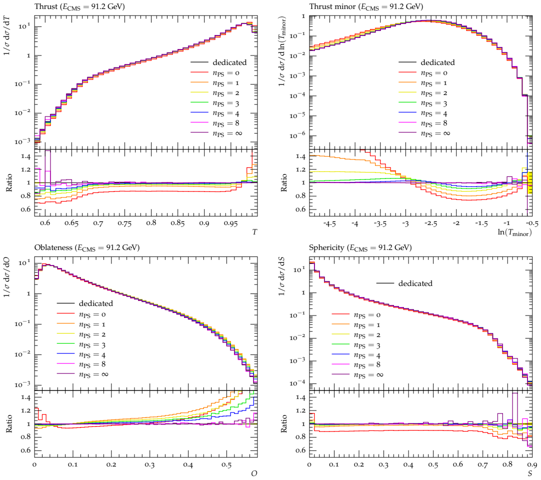
Closure tests: $e^+e^- \to$ hadrons @ LOPS



closure test with $n_{PS} = 0, 1, 2, 3, 4, 8, \infty$

- $\alpha_s(m_Z) = 0.120$
  $\downarrow$
  $\tilde{\alpha}_s(m_Z) = 0.128$
- n_{PS} needed obs. dependent

Closure tests: $e^+e^- \to$ hadrons @ LoPs



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NLOPS

- match hardest parton shower emission, use subtraction $(\mathrm{I},\ \mathrm{KP},\ \mathrm{D}_S)$ and pseudo-subtraction with evolution kernels D_A

$$
\begin{aligned}
\langle O\rangle^{\text{NLOPS}} = \int \mathrm{d}\Phi_B \; \Big[\mathrm{B}(\Phi_B) + \mathrm{VI}(\Phi_B) + \int \mathrm{d}x'_{a/b}\, \mathrm{KP}(\Phi_B, x'_{a/b}) \\
+ \sum_j \int \mathrm{d}\Phi_1^j \; (\mathrm{D}_{A,j} - \mathrm{D}_{S,j})\,(\Phi_B \cdot \Phi_1^j) \Big]\, \mathrm{PS}_{\mathrm{NLOPS}}(O, \Phi_B) \\
+ \int \mathrm{d}\Phi_R \; \Big[\mathrm{R}(\Phi_R) - \sum_j \mathrm{D}_{A,j}(\Phi_{B,j} \cdot \Phi_1^j) \Big]\; \mathrm{PS}(O, \Phi_R)
\end{aligned}
$$

- colour- and spin-correlated emission $\mathrm{PS}_{\mathrm{NLOPS}}$ and standard PS differ only through choice of splitting kernels, D_A/B vs. K
  $\rightarrow$ reweighting properties identical

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$$\left. + \sum_j \int \mathrm{d}\Phi_1^j \,(\mathrm{D}_{A,j} - \mathrm{D}_{S,j})\,(\Phi_B \cdot \Phi_1^j)\right] \mathrm{PS}_{\text{NLOPS}}(O, \Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \left[\mathrm{R}(\Phi_R) - \sum_j \mathrm{D}_{A,j}(\Phi_{B,j} \cdot \Phi_1^j)\right] \mathrm{PS}(O, \Phi_R)$$

$$\equiv \mathrm{H}_A$$

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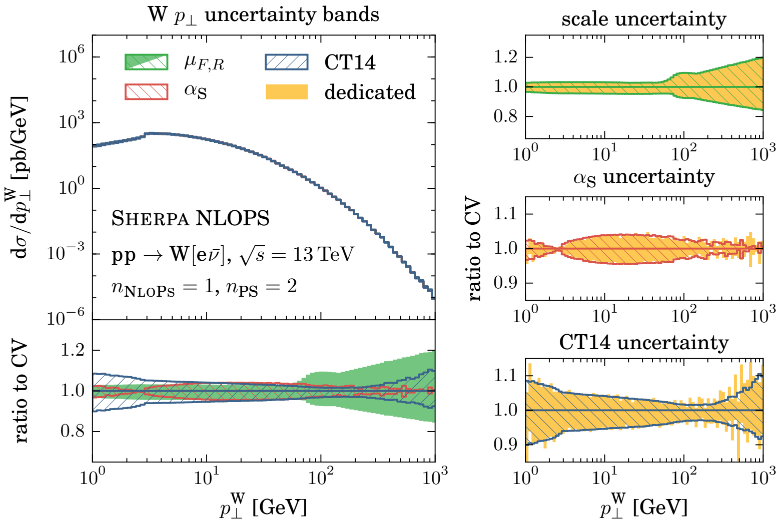
Closure tests: $pp \to W$ @ NLOPS



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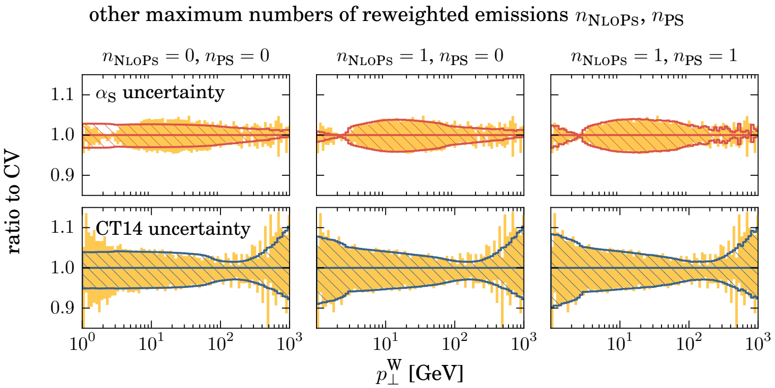

$\to$ reweighting two emission sufficient for this observable

Multijet merging

- basic idea: separate phase space into soft and hard region using some measure Q_n, use Φ_{n+1}-ME for $Q_n > Q_\text{cut}$
- restore resummation properties of parton shower in ME region through
  - identify would-be shower history through clustering using inversion of parton shower evolution as jet algorithm
    $\rightarrow$ flavour and initial state aware, on-shell $\rightarrow$ on-shell, probabilistic
  - $\{a_i, b_i, x_{a,i}, x_{b,i}, t_i\}$ ordered if $t_j < t_{j-1} < \ldots < t_1 < t_0 = \mu_{F,\text{core}}^2$
  - set scales as

$$\alpha_s^{n+j}(\mu_R^2) = \alpha_s^{n+e}(\mu_{R,\text{core}}^2) \prod_{i=1}^{j} \alpha_s^{1-\epsilon_i}(k_{\alpha_s} t_i)$$

  - include PDF ratios for every ordered emission

$$\prod_{i=1}^{j} \frac{f_{a_i}(x_{a,i}, k_f t_i)}{f_{a_{i-1}}(x_{a,i-1}, k_f t_i)} \prod_{i=1}^{j} \frac{f_{b_i}(x_{b,i}, k_f t_i)}{f_{b_{i-1}}(x_{b,i-1}, k_f t_i)}$$

  - include QCD and EW splitting functions to account for $pp \rightarrow Z + \text{jets}$ vs. $pp \rightarrow \text{jets} + Z$

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Multijet merging @ LO

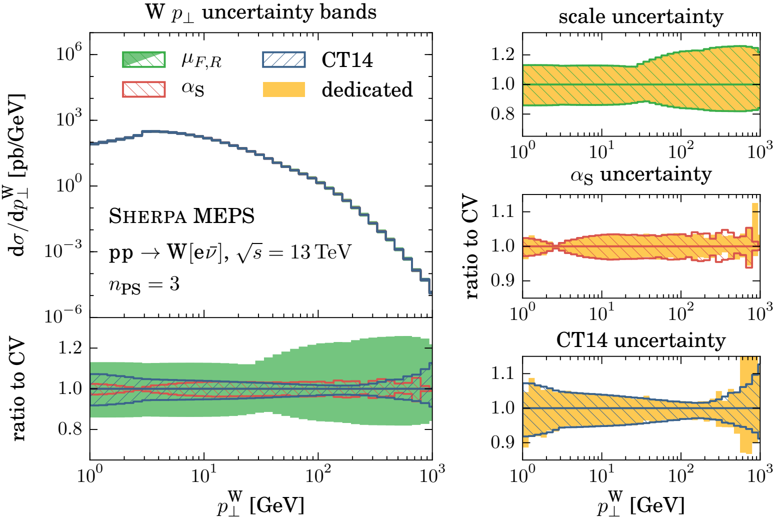
- in leading order merging

$$\langle O\rangle^{\text{MEPS}} = \sum_{j=0}^{j_{\max}} \int \mathrm{d}\Phi_j\, \mathrm{B}_j^{\text{merge}}(\Phi_j)\, \mathrm{PS}^{\text{vt}}(O,\Phi_j)$$

- standard PS replaced by vetoed truncated parton shower PS^{vt}
  $\rightarrow$ start evolution at core process, truncated evolution between reconstructed scales t_{i-1} and t_i:
  - $Q < Q_{\text{cut}}$ keep emission, restores resummation in t
  - $Q > Q_{\text{cut}}$ veto event, implements Sudakov weight
- in case of fully ordered history

$$\mathrm{B}_j^{\text{merge}}(\Phi_j) = \alpha_s^{n+j}(\mu_R^2) \prod_{i=1}^{j} \frac{f_{a_i}(x_{a,i}, k_f t_i)}{f_{a_{i-1}}(x_{a,i-1}, k_f t_i)}\, f_{a_0}(x_{a,0}, \mu_{F,\text{core}}^2) \times \prod_{i=1}^{j} \frac{f_{b_i}(x_{b,i}, k_f t_i)}{f_{b_{i-1}}(x_{b,i-1}, k_f t_i)}\, f_{b_0}(x_{b,0}, \mu_{F,\text{core}}^2)\, \mathrm{B}_j'(\Phi_j)$$

Closure tests: $pp \to W$ @ MEPs



Multijet merging @ NLO

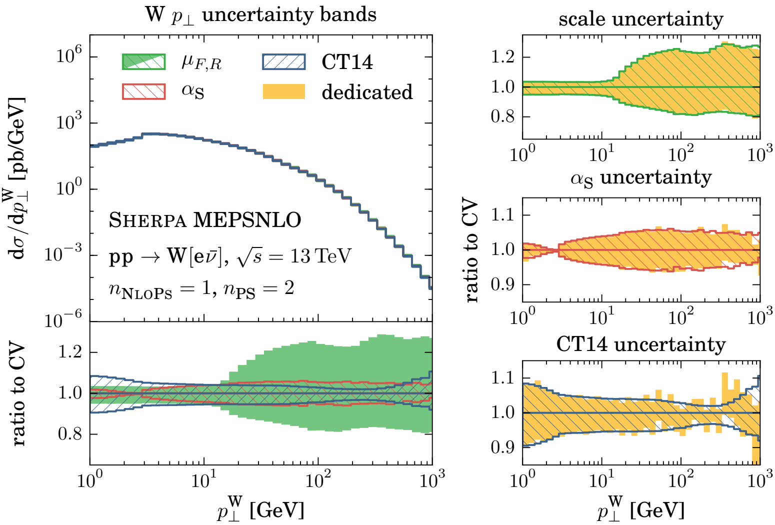
- proceeds schematically as at leading order

$$\langle O\rangle^{\text{MEPS@NLO}} = \sum_{j=0}^{j_{\max}} \Bigg[\int \mathrm{d}\Phi_j\, \overline{\mathrm{B}}_j^{\text{merge}}(\Phi_j)\, \mathrm{PS}^{\text{v}}_{\text{NLOPS}}(O,\Phi_j) + \int \mathrm{d}\Phi_{j+1}\, \mathrm{H}_{A,j}^{\text{merge}}(\Phi_{j+1})\, \mathrm{PS}^{\text{vt}}(O,\Phi_{j+1})\Bigg]$$

- $\mathcal{O}(\alpha_s)$ expansion of Sudakov weight subtracted in PS^{vt} through MC methods Höche, Krauss, MS, Siegert JHEP04(2013)027
- subtract $\mathcal{O}(\alpha_s)$ expansion of PDF ratios

$$-\sum_{i=1}^{j} \frac{\alpha_s(\mu_R^2)}{2\pi} \log\frac{t_{i-1}}{t_i} \left(\sum_{c=q,g} \int \frac{\mathrm{d}x'_{a,i}}{x'_{a,i}}\, P_{ac}(x'_{a,i})\, f_c(\tfrac{x_{a,i}}{x'_{a,i}}, k_f t_i) + \sum_{d=q,g} \int \frac{\mathrm{d}x'_{b,i}}{x'_{b,i}}\, P_{bd}(x'_{b,i})\, f_d(\tfrac{x_{b,i}}{x'_{b,i}}, k_f t_i)\right) \alpha_s^{n+j}(\mu_R^2)\, \mathrm{B}'_j(\Phi_j)$$

Closure tests: $pp \to W$ @ MEPS@NLO



Multijet merging @ NLO

- supplement MEPS@NLO with LO MEs of higher multiplicity

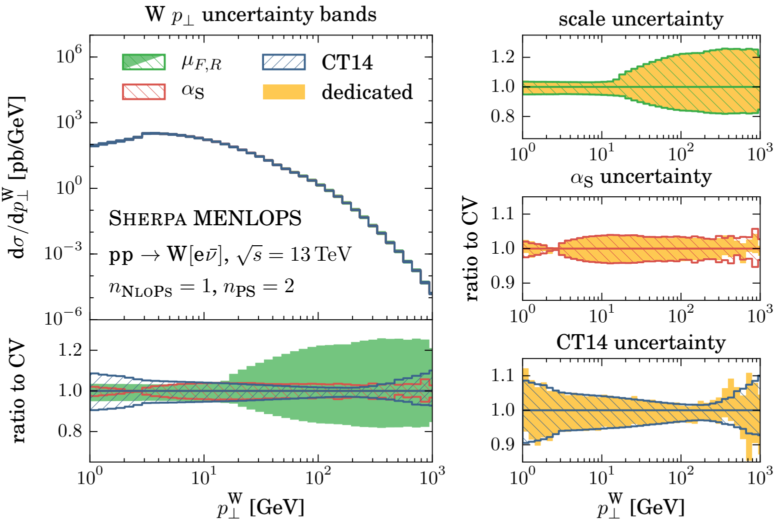
$$\langle O\rangle^{\text{MEPS@NLO+MENLOPS}} = \sum_{j=0}^{j_{\max}^{\text{NLO}}} \Bigg[\int \mathrm{d}\Phi_j\, \overline{\mathrm{B}}_j^{\text{merge}}(\Phi_j)\, \mathrm{PS}^{\text{v}}_{\text{NLOPS}}(O,\Phi_j) + \int \mathrm{d}\Phi_{j+1}\, \mathrm{H}_{A,j}^{\text{merge}}(\Phi_{j+1})\, \mathrm{PS}^{\text{vt}}(O,\Phi_{j+1})\Bigg] + \sum_{j=j_{\max}^{\text{NLO}}+1}^{j_{\max}} \int \mathrm{d}\Phi_j\, k_{j_{\max}^{\text{NLO}}}(\Phi_{j_{\max}^{\text{NLO}}+1}(\Phi_j))\, \mathrm{B}_j^{\text{merge}}(\Phi_j)\, \mathrm{PS}^{\text{vt}}(O,\Phi_j)$$

with

$$k_m(\Phi_{m+1}) = \frac{\overline{\mathrm{B}}_m(\Phi_m)}{\mathrm{B}_m(\Phi_m)}\left(1-\frac{\mathrm{H}_{A,m}(\Phi_{m+1})}{\mathrm{R}_m(\Phi_{m+1})}\right)+\frac{\mathrm{H}_{A,m}(\Phi_{m+1})}{\mathrm{R}_m(\Phi_{m+1})}$$

- differential K-factor moulds B_{m+1} into NLOPS result of Φ_m, reduces merging systematics

Closure tests: $pp \to W$ @ MeNLoPs



Conclusions

- all types of event generation in SHERPA can be reweighted
  $\rightarrow$ LO, NLO, LOPS, NLOPS, MEPS, MEPS@NLO, MENLOPS
- includes uncertainties due to
  scales
  - μ_R, μ_F in matrix elements
  - prefactors k_{α_s}, k_f in parton shower

  parametrisations
  - α_s through $\alpha_s(m_Z)$
  - PDFs through parametrisation (set, eigenvector/replica)
- does not yet include variation of
  - merging parameter Q_{cut}
  - parton shower starting scale μ_Q
  - evolution variable t
  - functional form of resummation kernel K
  - recoil scheme
- preliminary version (ME only) in SHERPA-2.2, full in SHERPA-2.3

Timings in $pp \to \ell^+\ell^- + \leq 4$jets (ME scale/PDF only)

weighted events

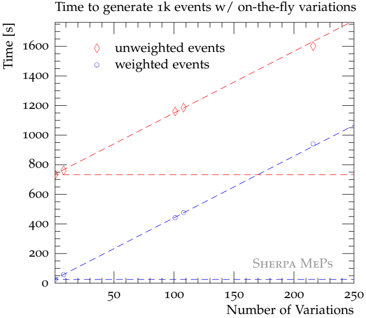
- low baseline per event timing (25s/1k)
- constant offset per computed variation

$\Rightarrow$ 217 vars. $\to$ factor 38

(partially) unweighted events

- high baseline per event timing (730s/1k)
- constant offset per computed variation

$\Rightarrow$ 217 vars. $\to$ factor 2.2



$\mu_{R\|F}$	$\to$	7
PDF (NNPDF30)	$\to$	100
$\mu_{R\|F}$+PDF	$\to$	107
PDF4LHC (old)	$\to$	217

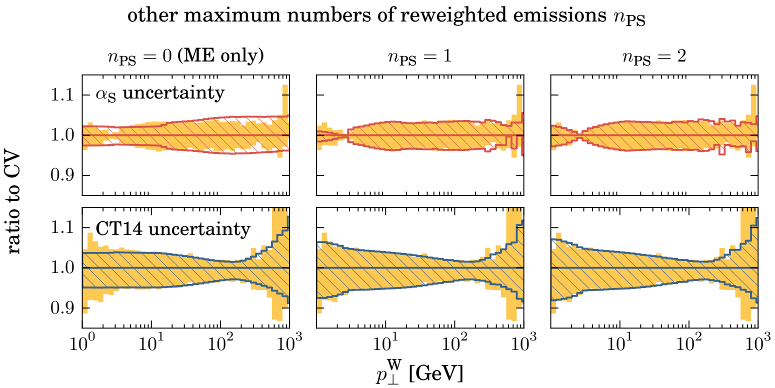
$\to$ time to compute variations independent of event generation mode

$\Rightarrow$ **huge gain for standard (partially) unweighted events**

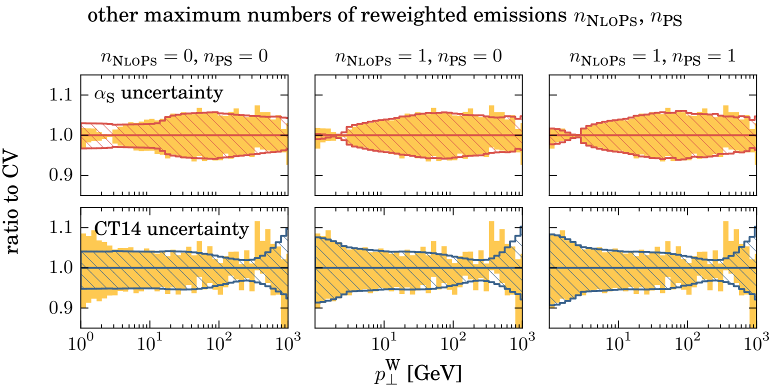
Thank you for your attention!

Backup

Closure tests: $pp \to W$ @ MEPS



Closure tests: $pp \to W$ @ MEPS@NLO



Closure tests: $pp \to W$ @ MENLOPS

other maximum numbers of reweighted emissions $n_{\text{NLOPS}}, n_{\text{PS}}$