Perturbative Uncertainties in Unitarized NLO Merging

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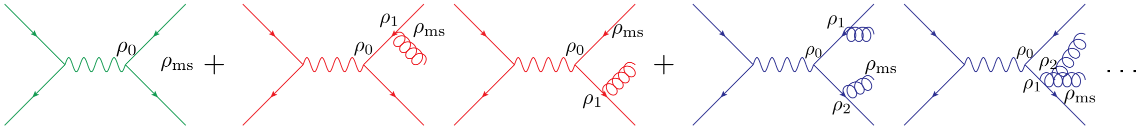
Introduction

- Recent study [LG, Prestel (2020)]
- Discuss perturbative uncertainty in unitarized NLO multi-jet merged predictions
- Available: Scale variations in hard process generation and parton shower
- Considered here:
  - Combination of renormalization scale variations between hard process and parton shower
  - Corresponding renormalization scale variations in merging weights
  - Variation of UNLOPS merging scheme, compared to scale variation

$\Rightarrow$ How does uncertainty on merging prescription compare to scale variation?

Multi-jet Merging: Illustration of CKKWL [Lönnblad (2001)] [Catani, Krauss, Kuhn, Webber (2001)]



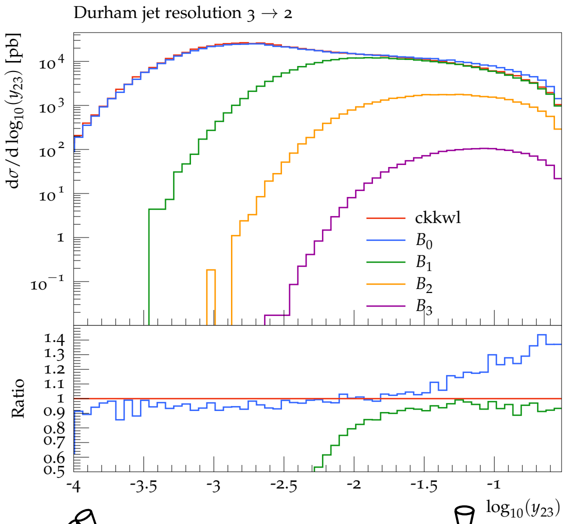
Combine MEs with different multiplicities, avoid overlap by reweighting

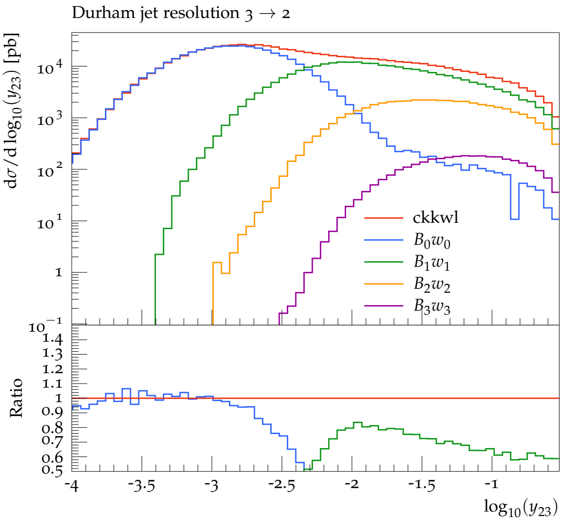
$$\langle \mathcal{O} \rangle = \int d\phi_0 \left\{ \mathcal{O}_0 B_0 w_0 + \int d\phi_1 \mathcal{O}_1 B_1 w_1 + \int d\phi_1 \int d\phi_2 \mathcal{O}_2 B_2 w_2 \right\}$$

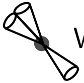
with the weights

$$w_0 = \Pi_0(\rho_0, \rho_{\rm ms})\,, \;\; w_1 = \Pi_0(\rho_0, \rho_1) \frac{\alpha_s(\rho_1)}{\alpha_s(\mu_R)} \Pi_1(\rho_1, \rho_{\rm ms})\,,$$

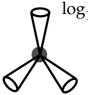
$$w_2 = \Pi_0(\rho_0, \rho_1) \frac{\alpha_s(\rho_1)}{\alpha_s(\mu_R)} \Pi_1(\rho_1, \rho_2) \frac{\alpha_s(\rho_2)}{\alpha_s(\mu_R)}$$







Wrong without weights



All plots generated with MG5_aMC@NLO + Pythia8

arXiv:1405.0301 arXiv:hep-ph/0603175

Unitarized Merging: UMEPS [Lönnblad, Prestel (2012)][Plätzer (2012)]

- Problem: CKKWL merging does not preserve inclusive cross section given by B_0 sample
- Fix by rewriting no-emission probability

$$B_0 w_0 = B_0 \Pi_0(\rho_0, \rho_1) = B_0 - \int_{\rho_1}^{\rho_0} \mathrm{d}\rho B_1(\rho) w_1$$

- Observables in unitarized multi-jet merging (UMEPS):

$$\langle \mathcal{O} \rangle = \int d\phi_0 \left\{ \mathcal{O}_0 \left[B_0 - \int B_1 w_1 \right] \right. \\ \left. + \int d\phi_1 \mathcal{O}_1 B_1 w_1 \right\}$$

How Reliable are our Predictions?

- Best answer: higher order calculations in α_s
- Strong coupling α_s depends on "hardness" scale ρ
- Choice of scale does not spoil fixed order accuracy, since $\alpha_\mathrm{s}(\rho') = \alpha_\mathrm{s}(\rho) + \mathcal{O}(\alpha_\mathrm{s}^2)$
- Use ρ variations by factor $1/2$ and 2 to estimate higher order effects $\Rightarrow$ scale uncertainties

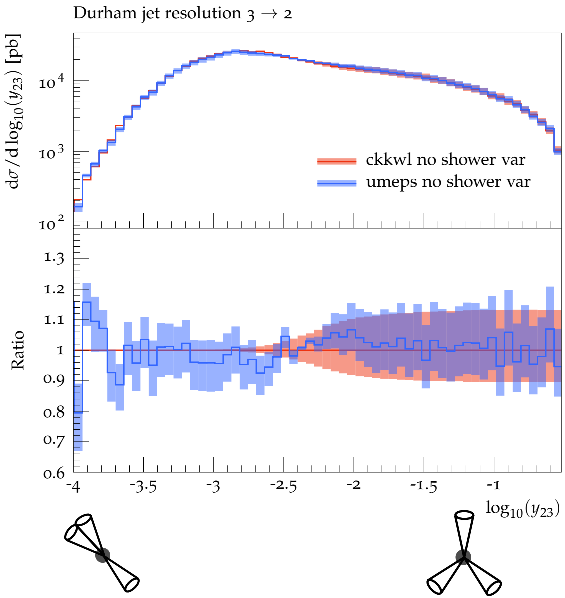
For consistency, do variation in three components of calculation simultaneously:

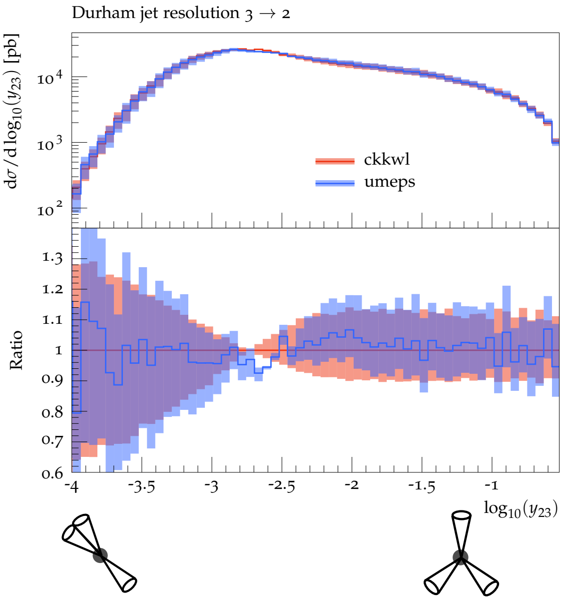
Hard process:
$\alpha_\mathrm{s}(\mu_\mathrm{R})$ in matrix elements

Parton shower:
$\alpha_\mathrm{s}(\rho_i)$ in emissions

Merging weights:
No-emission probabilities and emissions

$$w_1 = \Pi_0(\rho_0, \rho_1; b)\frac{\alpha_\mathrm{s}(b\rho_1)}{\alpha_\mathrm{s}(b\mu_\mathrm{R})}$$


Durham jet resolution 3 → 2
dσ / d log10(y23) [pb]
ckkwl no shower var
umeps no shower var
Ratio
log10(y23)


Durham jet resolution 3 → 2
dσ / d log10(y23) [pb]
ckkwl
umeps
Ratio
log10(y23)

NLO Matching

MC@NLO matching prescription: combine NLO cross section with parton shower:

$$\begin{aligned}\langle\mathcal{O}\rangle_{\mathrm{MC@NLO}} = &\int \mathrm{d}\phi_n (B_n + V_n + B_n \otimes I_1)\mathcal{F}_n(\mathcal{O},\phi_n) && \text{Born + subtracted virtual}\\ &+ \int \mathrm{d}\phi_{n+1}(B_n \bar{P}_{n+1} - B_n \otimes D_1)\mathcal{F}_n(\mathcal{O},\phi_{n+1})) && \text{Shower virtual - subtraction}\\ &+ \int \mathrm{d}\phi_{n+1}(B_{n+1} - B_n \bar{P}_{n+1})\mathcal{F}_{n+1}(\mathcal{O},\phi_{n+1}) && \text{Real - shower real}\end{aligned}$$

- $B_n + V_n + B_{n+1}$ NLO cross section
- Subtraction: Can evaluate cross section numerically
- Shower subtraction: Can generate events

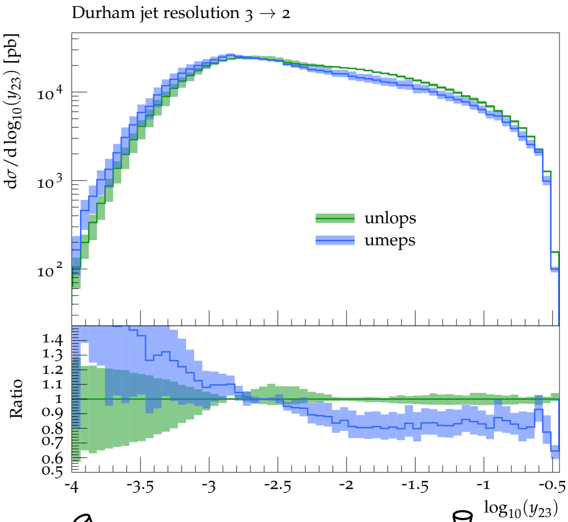
Variation of $\alpha_\mathrm{s}(\mu_\mathrm{R})$ here $\rightarrow$ do same in shower to exactly cancel shower subtraction

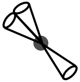
Multi-jet Merging at NLO

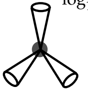
- UNLOPS [Lönnblad, Prestel (2013)]: Combine NLO matrix elements in unitary merging
- Subtract $\mathcal{O}(\alpha_s)$ from weights to preserve perturbative accuracy

$$\langle \mathcal{O} \rangle = \int d\phi_0 \Big\{ \mathcal{O}_0 \Big[\bar{B}_0 - \int_S \bar{B}_{1\to 0} - \int_S B_{1\to 0} \big(w_1 - w_1|_{\mathcal{O}(\alpha_s)} \big) \Big] + \int d\phi_1 \mathcal{O}_1 \Big[\bar{B}_1 + B_1 \big(w_1 - w_1|_{\mathcal{O}(\alpha_s)} \big) \Big] \Big\}$$

with $\bar{B}$ subtracted NLO cross sections, w CKKW-L weight as before







- Central prediction changes
- Scale variation band reduces

Freedom in Choice of Merging Scheme

Merging scheme should

- preserve fixed order quantum interference model
- preserve parton shower state evolution model

Define three valid variants of UNLOPS, look at 1 jet contribution

UNLOPS-1

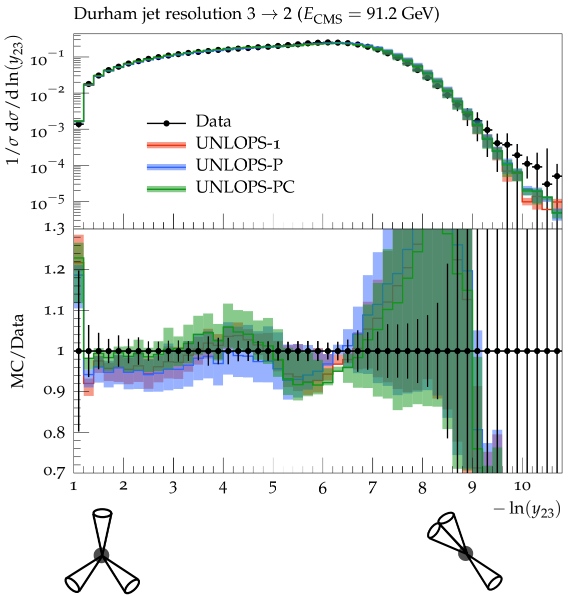
$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1 |_{\mathcal{O}(\alpha_s)} \right]$$

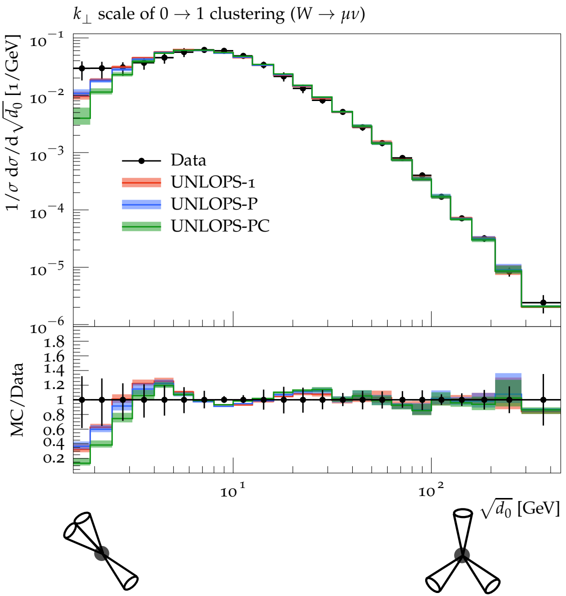
UNLOPS-P

$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1 |_{\mathcal{O}(\alpha_s)} \right] \Pi_0(\rho_0, \rho_1, b)$$

UNLOPS-PC

$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1 |_{\mathcal{O}(\alpha_s)} \right] \Pi_0(\rho_0, \rho_1, b) \frac{\alpha_s(b\rho_1)}{\alpha_s(b\mu_R)}$$


Durham jet resolution 3 → 2 (E_{CMS} = 91.2 GeV)
$1/\sigma\, d\sigma/d\ln(y_{23})$
Data
UNLOPS-1
UNLOPS-P
UNLOPS-PC
MC/Data
$-\ln(y_{23})$


$k_\perp$ scale of 0 → 1 clustering ($W \to \mu\nu$)
$1/\sigma\, d\sigma/d\sqrt{d_0}$ [1/GeV]
Data
UNLOPS-1
UNLOPS-P
UNLOPS-PC
MC/Data
$\sqrt{d_0}$ [GeV]

Summary

- Scale variations in both ME and PS available: combine in matched predictions
- Take variation into account in merging weights
- Freedom in choice of NLO merging scheme $\Rightarrow$ uncertainty on merged prediction
- Scheme uncertainty not always negligible
- Implemented automated scale and merging scheme variation in Pythia 8.303