Tackling the Uncertainties of Event Generators

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Paper I: High Dimensional Parameter Tuning for Event Generators

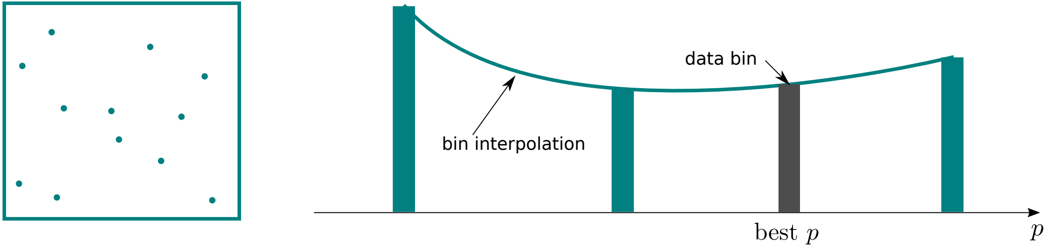
Johannes Bellm and Leif Gellersen

e-Print: arXiv:1908.10811 [hep-ph]

Eur.Phys.J.C 2020 80, 54

How to Tune

- Generate MC pseudodata $f_i(\vec{p})$, compare to experimental data bin $\mathcal{R}_i$
- Iterative MC event generation slow → Use bin-wise parametrization of MC generator response



- Minimize $\chi^2(\vec{p}) = \sum_i w_i \frac{(f_i(\vec{p}) - \mathcal{R}_i)^2}{\Delta_i^2}$, with data uncertainty Δ_i, bin weights w_i
- Professor: Python package for MC tuning, highly automated, includes validation tools
  arXiv:0907.2973, A. Buckley et al., 2009

AutoTunes

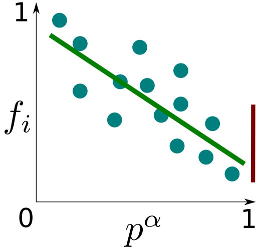
Problem

- Polynomial interpolation only possible for $\lesssim 10$ parameters
- Interpolation only good if ranges small enough
- χ^2 depends on weights → need to know data and generator

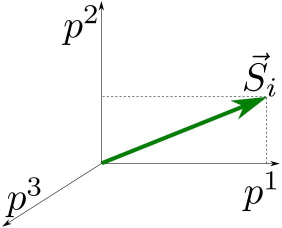
Goal

- Framework to reduce human interaction & make tune reproducible
- Tune many parameters at once: automatically divide into sub-tunes
- Set weights for observables automatically
- Allow for iterations with revised parameter ranges

AutoTunes: The Idea

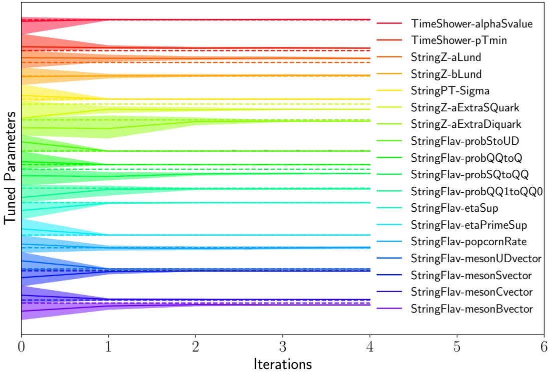


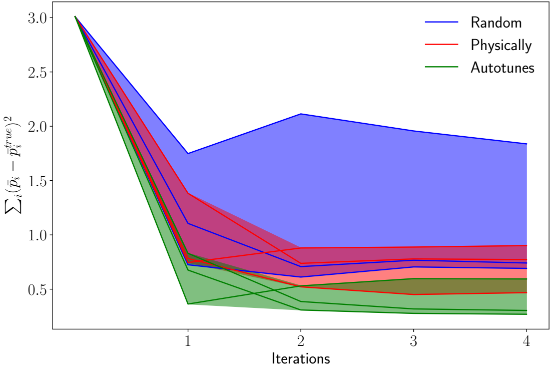
- Normalize each bin f_i and each parameter p^α to $[0,1]$
- Find slopes $\mathcal{S}_i^\alpha$
- $\vec{\mathcal{S}}_i$ vectors in parameter space
- Normalize: $\mathcal{N}_i^\alpha = \dfrac{\mathcal{S}_i^\alpha}{\sum_i \mathcal{S}_i^\alpha}$
- Find $\vec{\mathcal{J}} = (1,0,0,1,0,\ldots,1)$ that maximizes $\mathcal{M} = \sum_i (\vec{\mathcal{N}}_i \cdot \vec{\mathcal{J}})^2$
  → "Most correlated" subset of parameters: tune in one step
- Use weights $w_i = \dfrac{(\vec{\mathcal{N}}_i \cdot \vec{\mathcal{J}})^2}{\sum_\alpha \mathcal{N}_i^\alpha}$, emphasizes relevant data bins



Iterative Pythia Tune to Pythia Pseudodata

Try to reproduce − − − values, ≈ 6000 DOF & 18 parameters





Paper II: Scale and Scheme Variations in Unitarized NLO Merging

Leif Gellersen and Stefan Prestel

e-Print: arXiv:2001.10746 [hep-ph]

Phys.Rev.D 101 (2020) 11, 114007

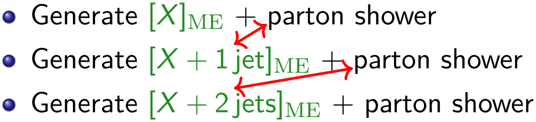
Multi-jet Merging

Combine strengths of Matrix Elements and Parton Showers

Experiments measure exclusive event: need to describe all emissions

- Describe hard emissions by fixed order predictions (including interference effects)
- Add further emissions from parton shower

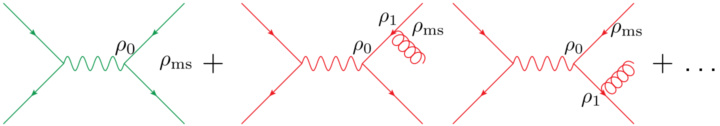
Want to improve PS emissions for more than hardest emission. Naive approach:



- Generate $[X]_{\mathrm{ME}}$ + parton shower
- Generate $[X + 1\,\text{jet}]_{\mathrm{ME}}$ + parton shower
- Generate $[X + 2\,\text{jets}]_{\mathrm{ME}}$ + parton shower
- ...

And combine everything into one sample. Does not work, double counting!
⇒ Forbid hard PS emissions, add weights to take no-emission probabilities and running coupling into account

Multi-jet Merging



- Combine MEs, avoid overlap by reweighting [Lönnblad (2001)] [Catani, Krauss, Kuhn, Webber (2001)]

$$\langle\mathcal{O}\rangle = \int d\phi_0 \left\{\mathcal{O}_0 B_0 w_0 + \int d\phi_1 \mathcal{O}_1 B_1 w_1 + \ldots\right\}, \quad w_1 = \Pi_0(\rho_0,\rho_1)\frac{\alpha_s(\rho_1)}{\alpha_s(\mu_R)}\Pi_1(\rho_1,\rho_{\rm ms})$$

- Preserve cross-section in unitarized merging [Lönnblad, Prestel (2012)] [Plätzer (2012)]

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

- Use next-to-leading order MEs [Lönnblad, Prestel (2013)]

$$\langle\mathcal{O}\rangle = \int d\phi_0 \left\{\mathcal{O}_0 \left[\bar{B}_0 - \int \bar{B}_1 - \int B_1(w_1 - w_1^{(0,1)})\right] + \int d\phi_1 \mathcal{O}_1 \left[\bar{B}_1 + B_1(w_1 - w_1^{(0,1)})\right]\right\}$$

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

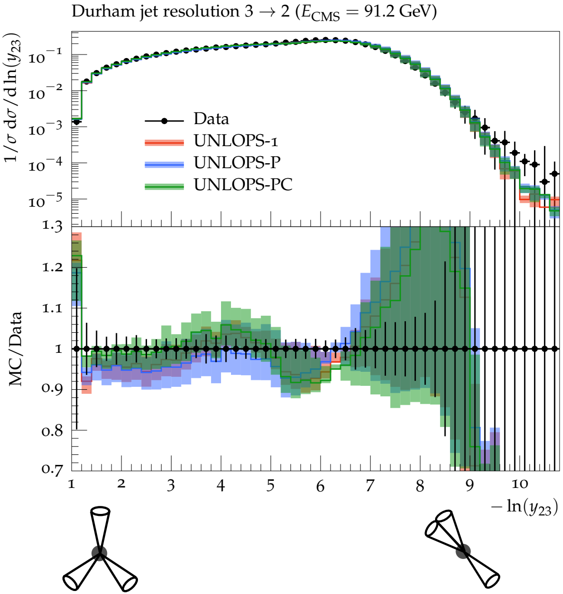
$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1^{(0,1)}\right]$$

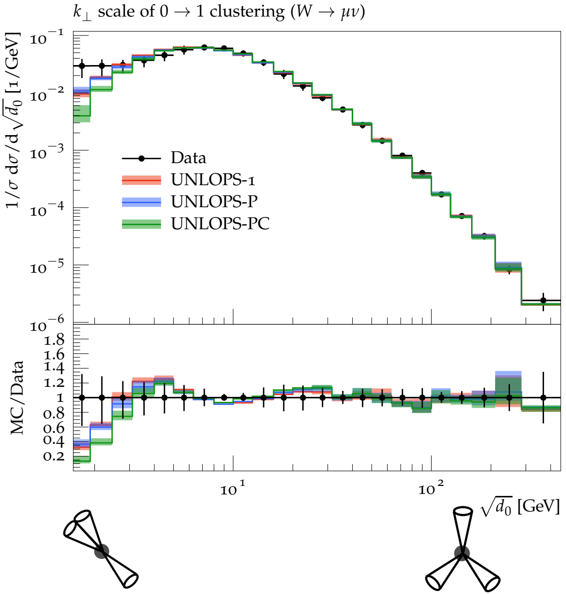
UNLOPS-P

$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1^{(0,1)}\right] \Pi_0(\rho_0, \rho_1, b)$$

UNLOPS-PC

$$B_1 w_1 + \left[\bar{B}_1 - B_1 w_1^{(0,1)}\right] \Pi_0(\rho_0, \rho_1, b) \frac{\alpha_s(b\rho_1)}{\alpha_s(b\mu_R)}$$


Durham jet resolution $3 \to 2$ ($E_{\mathrm{CMS}} = 91.2$ GeV)
$1/\sigma\, d\sigma/d\ln(y_{23})$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Data
UNLOPS-1
UNLOPS-P
UNLOPS-PC
MC/Data
1.3
1.2
1.1
1
0.9
0.8
0.7
1
2
3
4
5
6
7
8
9
10
$-\ln(y_{23})$


$k_\perp$ scale of $0 \to 1$ clustering ($W \to \mu\nu$)
$1/\sigma\, d\sigma/d\sqrt{d_0}$ [1/GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Data
UNLOPS-1
UNLOPS-P
UNLOPS-PC
MC/Data
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
10^{1}
10^{2}
$\sqrt{d_0}$ [GeV]

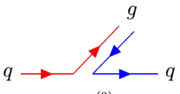
Paper III: Coloring Mixed QCD/QED Evolution

Leif Gellersen, Stefan Prestel and Michael Spannowsky

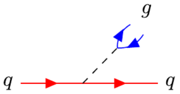
e-Print: arXiv:2109.09706 [hep-ph]

Fixed Color Parton Showers

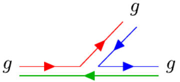
- Gluon emissions repaint quarks
- Usual approximation in PS: infinite number of colors
- Fixed color: $N_\mathrm{C} = 3$
- Modify splitting kernels to include all possible color flows



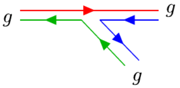
(c) $P^{(9)}_{rb}$



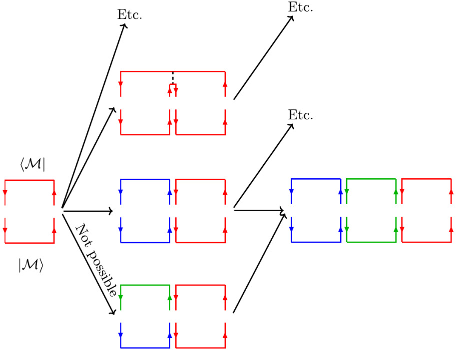
(f) $P^{(1)}_{rb}$



(i) $P^{(+)}_{rb}$



(l) $P^{(-)}_{gb}$



[Isaacson, Prestel (2019)]

Iterative Matrix Element Corrections [Fischer, Prestel (2017)]

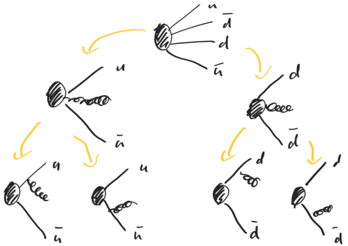
- Consider matrix element state $|\mathcal{M}(\Phi_0)|^2$
- Parton-shower produces branching according to $P(\Phi_1/\Phi_0)|\mathcal{M}(\Phi_0)|^2 \mathrm{d}\Phi_1$
- Apply MEC factor to correct weight of Φ_1 to full fixed-order matrix element

$$\mathcal{R}(\Phi_1) = \frac{|\mathcal{M}(\Phi_1)|^2}{\sum_{\Phi_0'} P(\Phi_1/\Phi_0')|\mathcal{M}(\Phi_0')|^2}$$

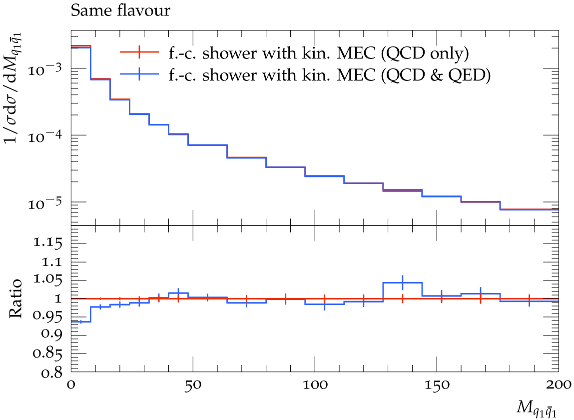
- Iterate, taking all possible PS histories into account

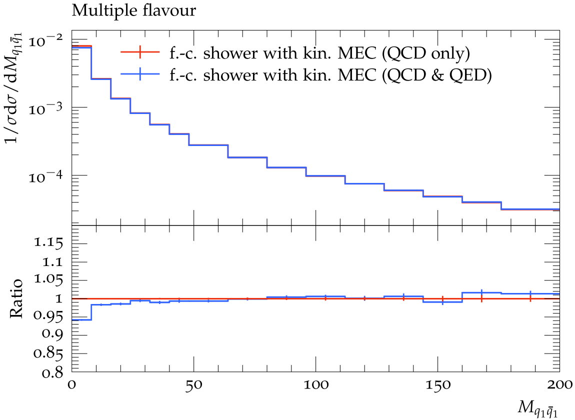
$$\mathcal{R}(\Phi_2) = \frac{|\mathcal{M}(\Phi_2)|}{\sum_{\Phi_1'} P(\Phi_2/\Phi_1')\mathcal{R}(\Phi_1') \sum_{\Phi_0'} P(\Phi_1'/\Phi_0')|\mathcal{M}(\Phi_0')|^2}$$

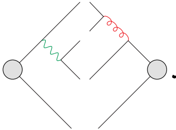
- Take FC and QED kernels into account



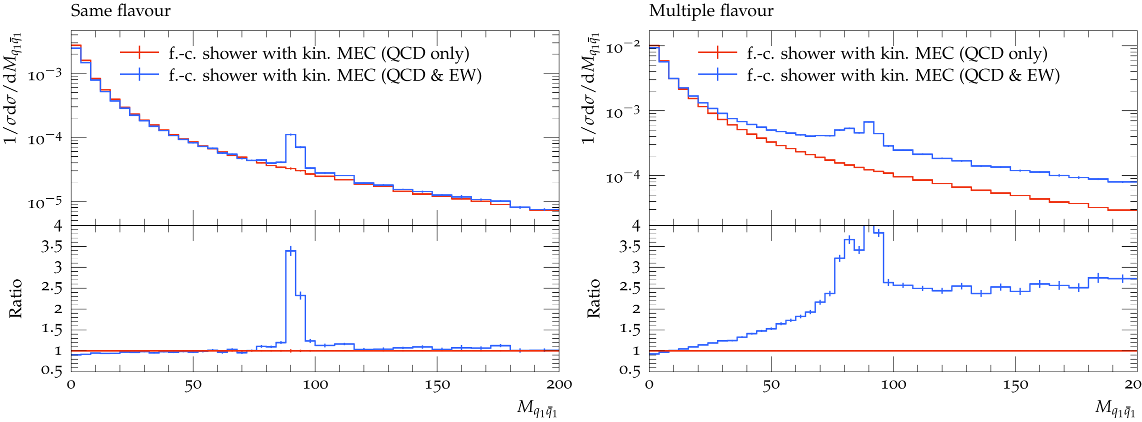
QCD/QED Interference


Same flavour


Multiple flavour

- QCD/QED interference only in same flavour case: $\mathcal{M}^*$  $\mathcal{M}$, here negligible

Electro-Weak Effects



- At high energies (here E_{CM} 1 TeV): EW W and Z boson effects large

Paper IV: Disentangling Soft and Collinear Effects in QCD Parton Showers

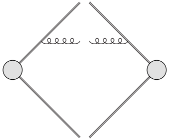
Leif Gellersen, Stefan Höche and Stefan Prestel

e-Print: arXiv:2110.05964 [hep-ph]

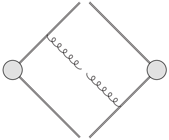
Parton Showers beyond Leading Order

- Leading order parton showers emit one parton at a time, e.g., 1 → 2 or 2 → 3

$$\mathcal{F}\big|_{1-\text{loop,coll}} \sim$$



$$, \quad \mathcal{F}\big|_{1-\text{loop,soft}} \sim$$



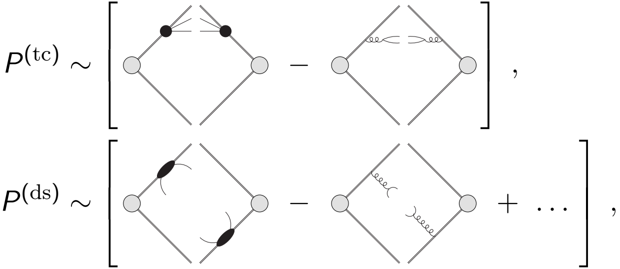
$$+ \; \ldots \; ,$$

- Improve description by including next higher order in splitting functions

$$P_{i\leftarrow j}(z,\alpha_\mathrm{s}) = P^{(0)}_{i\leftarrow j}(z) + \frac{\alpha_\mathrm{s}}{2\pi} P^{(1)}_{i\leftarrow j}(z) + \ldots$$

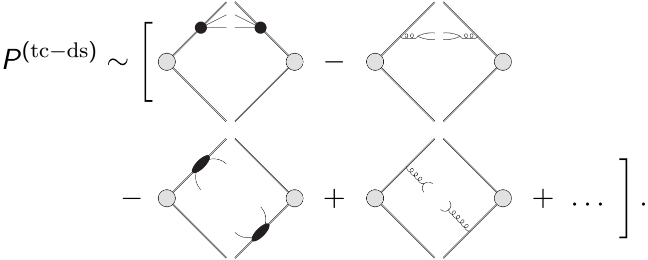
Double Soft and Triple Collinear Emissions

- Inclusion of double soft and triple collinear effects into NLO parton shower treated separately in [Höche, Prestel (2017), arXiv:1705.00742 [hep-ph]] and [Dulat, Höche, Prestel (2018), arXiv:1805.03757 [hep-ph]]
- Two structurally different approximations. Implemented in shower as additional kernel, avoiding double counting with LO shower by subtracting iterated LO shower

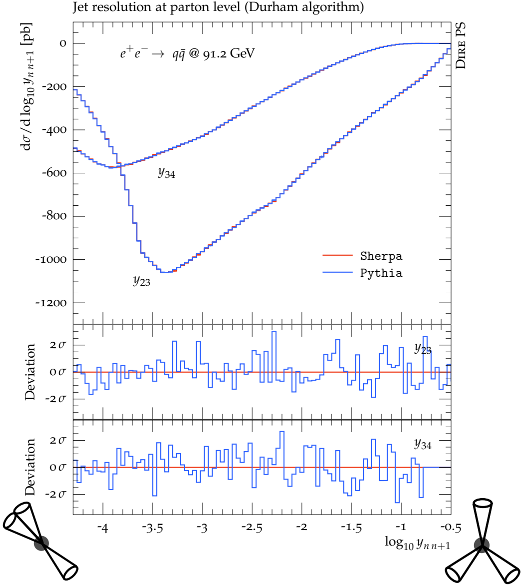


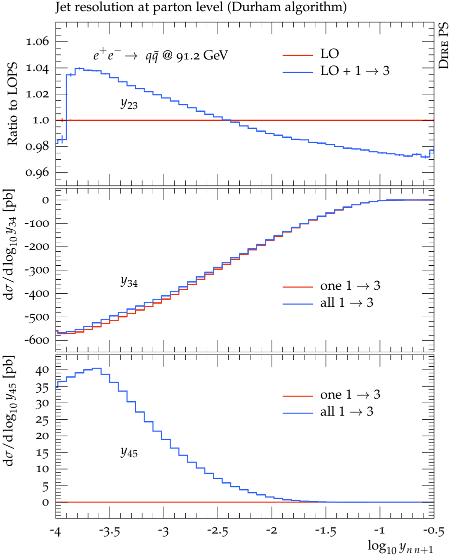
Combining Double Soft and Triple Collinear Emissions

- Need both double soft and triple collinear emissions in full NLO shower
- Remove overlap: include double soft, and subtract corresponding contribution from each triple collinear kernel



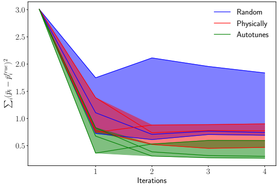
Validation and impact of soft-subtracted triple-collinear splittings

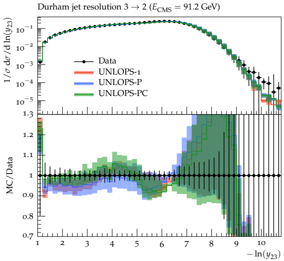


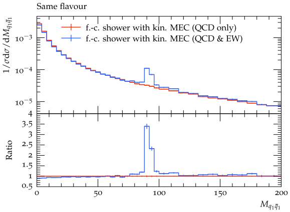


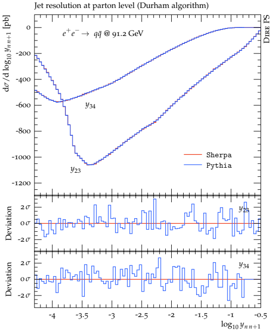
Summary

- MC event generators essential to predict exclusive final states at colliders
- Uncertainties due to choices (parameters, schemes, models) and approximations (LO, LC)









Thank you MCnet!