Colorful Event Deconstruction

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Introduction: Event Generation vs Event Deconstruction

Theory

QFT: Lagrangian formulation of physics

- Models encoded in Lagrangians
- Standard Model: $\mathcal{L}_{\text{SM}}$, BSM: $\mathcal{L}_{\text{BSM}}$

Experiments

Collider experiments with detectors

- Data in terms of individual events
- Measurement of observables

Linking theory & experiment: Hypothesis testing

Event generation

- Theory $\overset{\text{predict}}{\Rightarrow}$ pseudo-data
- Hypothesis test: Compare data vs pseudo-data

Event deconstruction

- Theory $\overset{\text{infer}}{\Leftarrow}$ data
- For individual events: likely to be signal or background?

Event Deconstruction [Soper, Spannowsky (2014)]

- Distinguish signal from background by constructing approximate likelihood ratio:

$$\chi = \frac{\mathcal{P}(\{k\}_N, \mathrm{signal})}{\mathcal{P}(\{k\}_N, \mathrm{background})}$$

- Estimate $\mathcal{P}(\{k\}_N, \mathrm{model})$ by convolution of PDFs and squared matrix element for hard process (model-dependent)
- Augment with parton shower approximation for rest of diagram

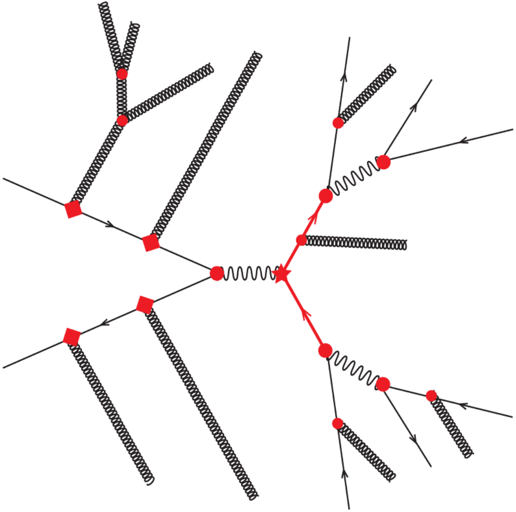
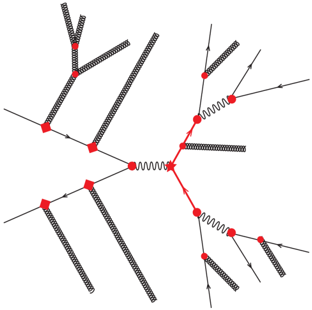


Figure: Shower history for $Z' \to t + \bar{t}$ signal event.

Event Deconstruction: Event Probabilities

- Complication: Many possible parton shower histories h_n and parton flavors f_n
- To get probability: need to sum over all possible configurations
- Simplification: Find J "fat" jets, group constituents into microjets $\{k\}_{N_n}^{(n)}$



$$\mathcal{P}(\{k\}_N, \mathrm{model}) = \sum_{f_1,\dots,f_J} \sum_{h_1,\dots,h_J} H(p(h_1), \cdots, p(h_J); f_1, \cdots, f_j) \\ \mathcal{P}(\{k\}_{N_1}^{(1)}, h_1, f_1) \times \cdots \times \mathcal{P}(\{k\}_{N_J}^{(J)}, h_J, f_J)$$

Event Deconstruction: Hypothesis Testing

- Test signal hypothesis on sample of experimental events: Number of events with large χ
- Simple cut based analysis: Select events with

$$\chi = \frac{\mathcal{P}(\{k\}_N, \text{signal})}{\mathcal{P}(\{k\}_N, \text{background})} > \chi_0$$

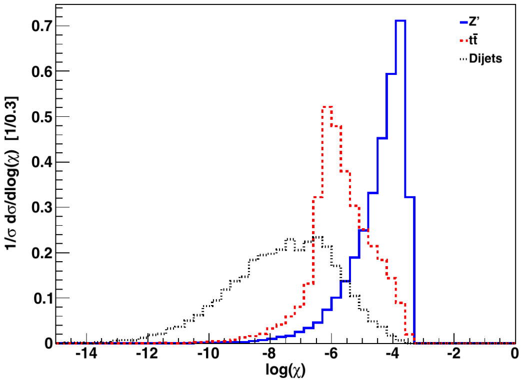


Figure: $log(\chi)$ distribution for signal Z' and backgrounds $t\bar{t}$ & dijet

Event Deconstruction: Limitations

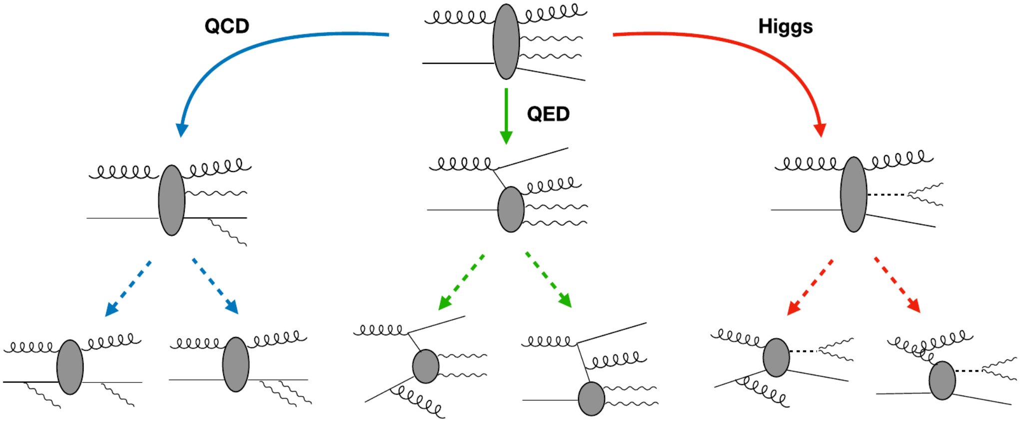
- Conceptionally simple, but computationally challenging
- Ways to improve:
  - Improve shower model to improve event deconstruction
  - Limited to one hard process signature, generalize to different multiplicities
- Idea: Combined matrix element and parton shower calculations also in matching & merging schemes for event generation: use those techniques for event deconstruction

HYTREES [Prestel, Spannowsky (2019)]

- Improvement of event deconstruction method
- Use CKKW-L merging style parton shower “history trees”, based on DIRE parton shower
- Improve by using hard matrix elements with multiple jet emissions
- Goal: Specify hypothesis + background model, provide data $\Rightarrow$ Tool discriminates

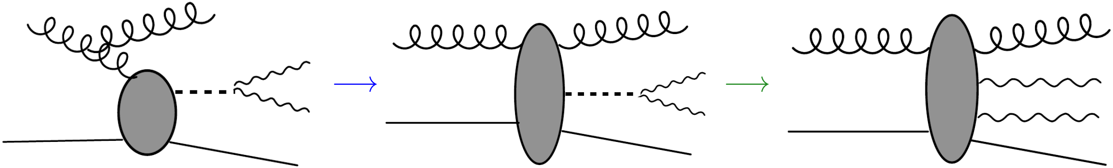
HYTREES: Construct all Shower Histories

Example: $H \to \gamma\gamma + \text{jets}$ with QCD and QED background



HYTREES: Probabilities

Closer look on rightmost branch:

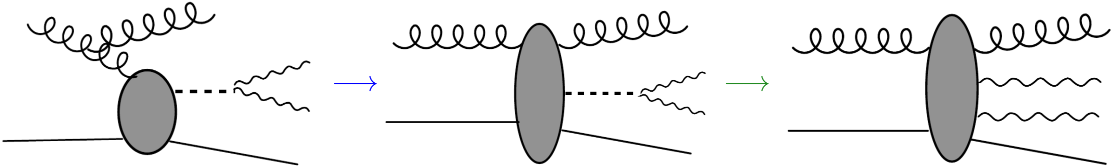


$$\mathcal{P} = |\mathcal{M}(hj)^{(1)}|^2 \otimes P_{H(1)} \otimes \left[\frac{|\mathcal{M}(Hjj)|^2}{|\mathcal{M}(hj)^{(1)}|^2 P_{H(1)} + |\mathcal{M}(hj)^{(2)}|^2 P_{H(2)}} \right]$$

$$\otimes P_H \otimes \left[\frac{|\mathcal{M}(\gamma\gamma jj)|^2|}{|\mathcal{M}(Hjj)|^2 P_H + |\mathcal{M}(\gamma\gamma j)|^2 P_{\mathrm{QED}} + |\mathcal{M}(\gamma jj)|^2 P_{\mathrm{QCD}}} \right]$$

HYTREES: Probabilities

Closer look on rightmost branch:



$$\mathcal{P} = |\mathcal{M}(hj)^{(1)}|^2 \otimes P_{H(1)} \otimes \left[\frac{|\mathcal{M}(Hjj)|^2}{|\mathcal{M}(hj)^{(1)}|^2 P_{H(1)} + |\mathcal{M}(hj)^{(2)}|^2 P_{H(2)}} \right]$$

$$\otimes P_H \otimes \left[\frac{|\mathcal{M}(\gamma\gamma jj)|^2|}{|\mathcal{M}(Hjj)|^2 P_H + |\mathcal{M}(\gamma\gamma j)|^2 P_{\mathrm{QED}} + |\mathcal{M}(\gamma jj)|^2 P_{\mathrm{QCD}}} \right]$$

Include CKKW-L weights for each path: $\mathcal{P} \to \mathcal{P}w = \mathcal{P}\Pi(t_{i-1}, t_i) \frac{\alpha(t_i)}{\alpha^{\mathrm{fix}}} \frac{f(x_{i-1}, t_{i-1})}{f(x_{i-1}, t_i)}$

Full Color Showers

- Dipole showers based on soft and collinear limits

$$|\mathcal{M}_{n+1}|^2 \simeq - \sum_{\tilde{ij},\tilde{k}\neq\tilde{ij}} \langle \mathcal{M}_n | \frac{\mathbf{T}_{\tilde{k}} \cdot \mathbf{T}_{\tilde{ij}}}{\mathbf{T}^2_{\tilde{ij}}} \mathcal{V}_{\tilde{ij},\tilde{k}} | \mathcal{M}_n \rangle \approx \sum_{\tilde{ij},\tilde{k}\in \mathrm{LC}} \langle \mathcal{M} | \mathcal{M} \rangle \mathcal{V}_{\tilde{ij},\tilde{k}}$$

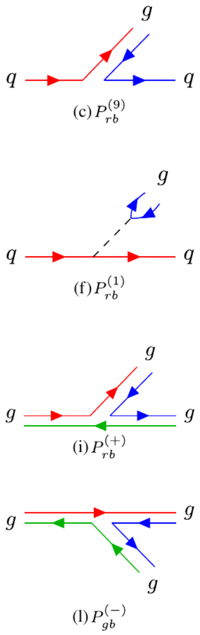
- Simplification by $N_C \to \infty$ and discarding spin correlations
- Full color shower: undo $N_C \to \infty$ approximation, include color correlator $\langle M | \frac{\mathbf{T}_{\tilde{k}} \cdot \mathbf{T}_{\tilde{ij}}}{\mathbf{T}^2_{\tilde{ij}}} | \mathcal{M} \rangle$
- Details and implementations available, e.g. [Nagy, Soper (2007)], [Plätzer, Sjödahl (2012)], [Forshaw, Holugin, Plätzer (2019)]

Full Color Showers

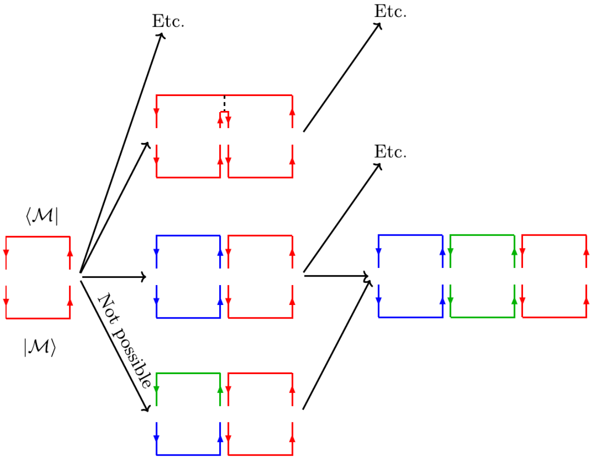
- Use color-flow basis [Maltoni, Paul, Stelzer, Willenbrock (2003)], as in [Martínez, Angelis, Forshaw, Plätzer, Seymour (2018)]
- Basis tensors denote flow of color from one leg to another

$$|\sigma\rangle = \left| \begin{matrix} 1 & 2 & \cdots & n \\ \sigma(1) & \sigma(2) & \cdots & \sigma(n) \end{matrix} \right\rangle = \delta^{c_1}_{\bar{c}_{\sigma(1)}} \delta^{c_2}_{\bar{c}_{\sigma(2)}} \cdots \delta^{c_n}_{\bar{c}_{\sigma(n)}}$$

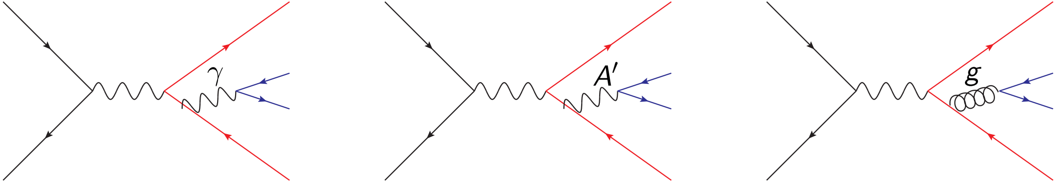
- Color operators decomposed as $\mathbf{T}_i = \lambda_i \mathbf{t}_{c_i} - \bar{\lambda}_i \bar{\mathbf{t}}_{\bar{c}_i} - \frac{1}{N_C}(\lambda_i - \bar{\lambda}_i)\mathbf{s}$
- $\mathbf{t}$, $\bar{\mathbf{t}}$, and $\mathbf{s}$ insert color-anticolor pair, different connections
- Color variables: Quark ($\lambda = \sqrt{T_R}$, $\bar{\lambda}_i = 0$)), antiquark ($\lambda = 0$, $\bar{\lambda}_i = \sqrt{T_R}$)), gluon ($\lambda = \sqrt{T_R}$, $\bar{\lambda}_i = \sqrt{T_R}$))



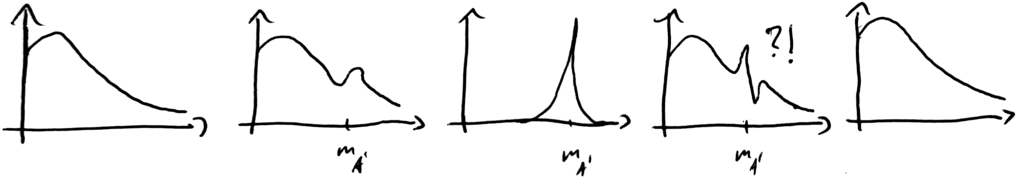
- Modify splitting kernels to include different color flows
- Allow all non-vanishing color flow combinations
- MC sample colour flow [Isaacson, Prestel (2019)]



Application: QCD & Dark Photons



Photon α_{em}^2 Dark photon: $\alpha_{\text{em}}^2 \epsilon^4$ Gluon α_s^2 / N_C^2

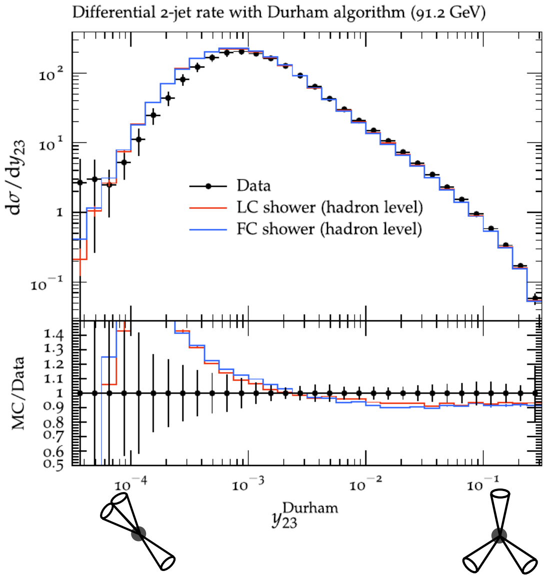


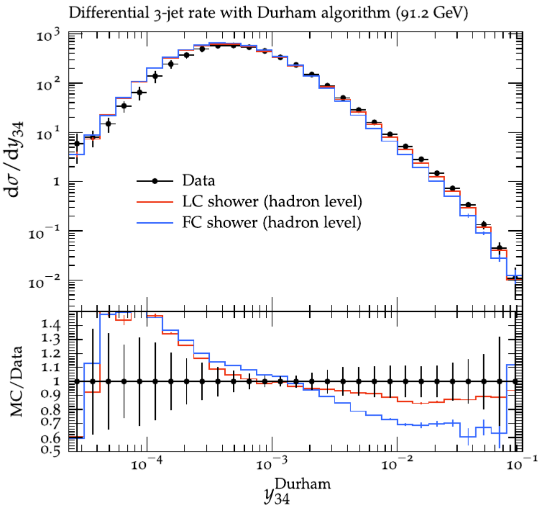
- Matrix element corrections allow to include signal background interference
- Effect from FC QCD larger than from QED?

Summary

- Event deconstruction: Distinguish signal and background based on likelihood ratio from ME and PS calculations directly
- Improve accuracy by HYTREES and full color treatment
- Does color enhance or deplete discrimination?
- Interesting for searches at (future) electron positron colliders

Backup





[Isaacson, Prestel (2019)]