Two approaches to hadronization reweighting

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On behalf of the **MLhad collaboration**

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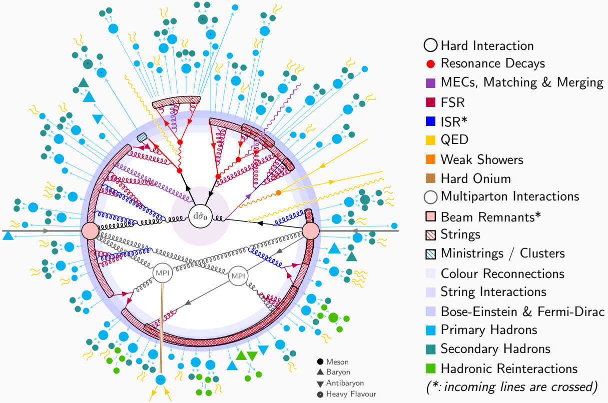
Hadronization reweighting: the “what” and “why” (arXiv:2203.11601)

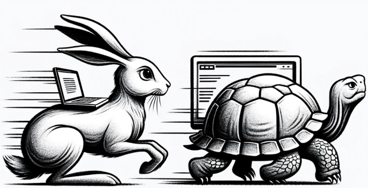
- Necessary component for th/ex comparisons.
- Interesting in its own right: non-perturbative QCD.



- Practical: computational demand rising.
- Exploratory: 1-1 implementations limiting.

Hadronization is fast... but slow!

- Vanilla hadronization is quick compared to e.g.. ME generation, slow compared to e.g.. PS.
    1. Rare hadronic final states (rare baryons, correlations,...).
    2. Many parameters, tuning hypercube dimensionality.
    3. Detector simulation very expensive in parameter scans.
- Solution: Throw more compute at the problem!



- This talk: hadronization reweighting to solve the problems.
    1. The string hadronization model and algorithm.
    2. Reweighting kinematics.
    3. Reweighting flavour.
    4. Results & outlook.

String hadronization at a glance (Phys.Rept. 97 (1983) 31-145)

- Non-perturbative Lund strings $\kappa \approx 1$ GeV/fm.

- Several parameters;
  - Usual parton shower.
  - Kinematics: a, b, $\sigma_{p_\perp}$.
  - Quark/diquark flavour selection: ρ, ξ, x, y.
  - Hadron spin + η, η' suppression.
  - Specialized models (baryons...).
  - More for excited states, usually disabled.

Governing equations

Longitudinal kinematics: $f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$

Flavour and $p_\perp$: $\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}^2 p_\perp} \propto \exp\left(-\pi m_{\perp,q}^2/\kappa\right)$

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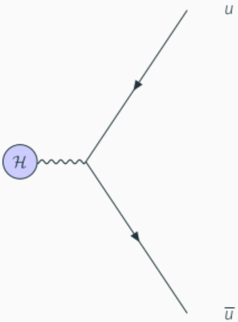

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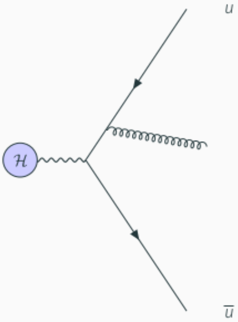

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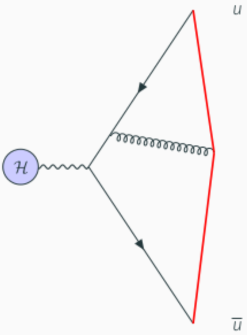

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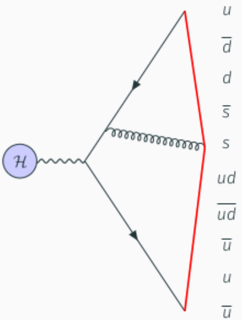

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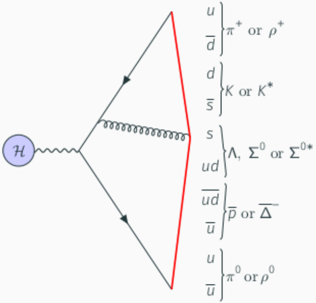

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The string break algorithm

- Basic algorithm unchanged since the 1980s.
- Given a partonic state, map into hadronic state, unit weight.
- `for` each string:
  1. Select randomly one end or the other.
  2. Pick the hadron flavour.
     2.1 Pick string break flavour.
     2.2 Force suppression according to SU(6) CG.
     2.3 Possibly `break`.
  3. Pick transverse momentum.
  4. Pick z and construct full hadron momentum.
  5. If energy/momentum used up, `break`.
- Result: Output which looks like measured "events".
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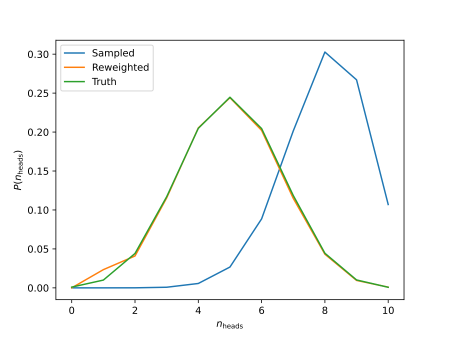
Reweighting: A pedagogical example

- Simple MC: simulate fair coin with weighted coin.
- Sample statistics on “heads”, don’t want to throw half the “events”.
- Let P(“heads”) = 0.8 instead of 0.5, and reweight at level of observable.



- Each “event” 10 tosses, 100k “events”, observable $P(n_{\text{heads}})$.

Kinematics reweighting: accept-reject (2308.13459)

- Sample z from $f(z)$. Continuous distribution, standard Accept/Reject algorithm. $f_{\mathrm{reject}} = 1 - f_{\mathrm{accept}}$ (unitarity).

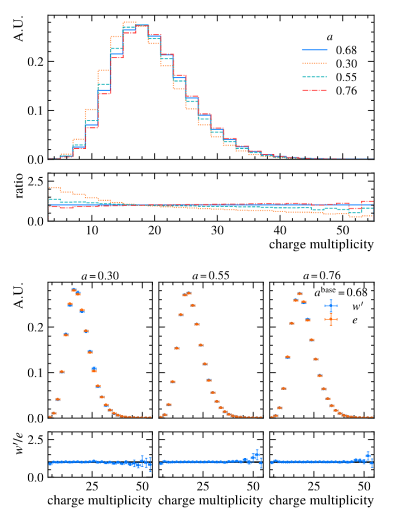
$$f_{\mathrm{accept}}(z, c_i) \equiv \frac{f(z, c_i)}{f_{\max}(c_i)} \leq 1; z_{\mathrm{trial}} \leftarrow R_1; \text{accept iff } f_{\mathrm{accept}}(z_{\mathrm{trial}}) > R_2.$$

- Now $c_i \mapsto c_i'$. Generate with c_i, weight maps to alternative.

$$w = \prod_{j \in \mathrm{accepted}} \frac{f(z_j, c_i')}{f(z_j, c_i)} \prod_{k \in \mathrm{rejected}} \frac{f_{\max}(c_i) - f(z_k, c_i')}{f_{\max}(c_i') - f(z_k, c_i)}$$

- Standard technique for PS variations.
- Reweighting $p_\perp$ analytically.
- Result: reweight to alternate reality c_i, even after detector simulation. Note c_i' must be selected *a priori*.

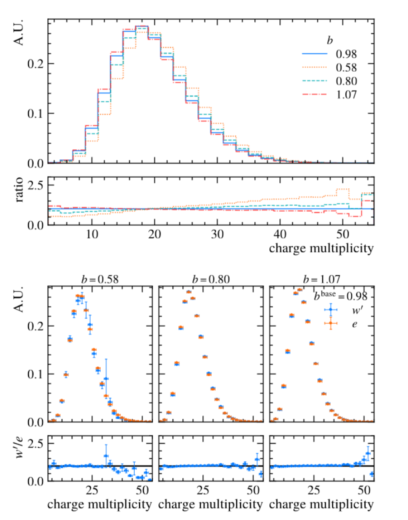
Kinematics reweighting: results I (2308.13459)



- Charged multiplicity, different values of a.
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: e-curves explicitly generated with a', w'-curves reweighted from base a to a'.

- More results in the paper!

Kinematics reweighting: results II (2308.13459)



- Charged multiplicity, different values of b.
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: e-curves explicitly generated with b', w'-curves reweighted from base b to b'.

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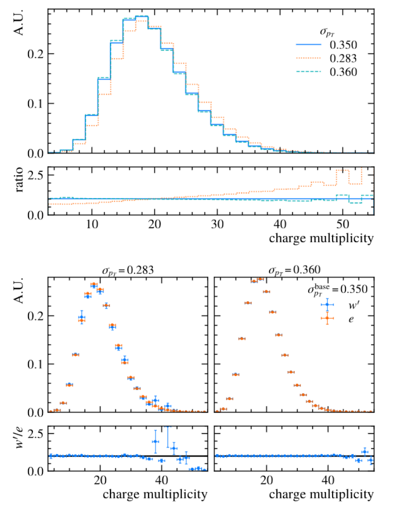
Kinematics reweighting: results III (2308.13459)



- Charged multiplicity, different values of $\sigma_{p_\perp}$.
- Top: Truth distribution, effect on charged multiplicity (e^+e^-).
- Bottom: e-curves explicitly generated with $\sigma'_{p_\perp}$, w'-curves reweighted from base $\sigma_{p_\perp}$ to $\sigma'_{p_\perp}$.

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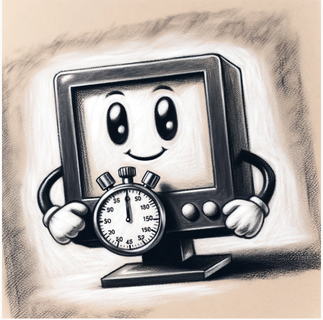
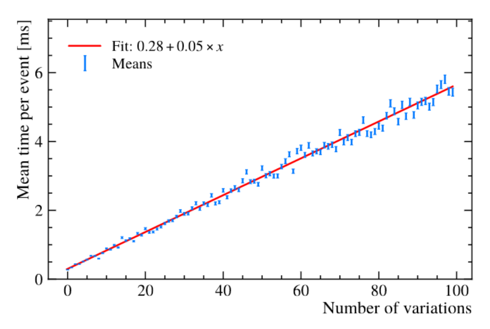
Kinematics reweighting: timing (2308.13459)

- Normal tuning: Each variation calculated separately.
- Very time consuming for many parameters!
- Same problem for error bands.



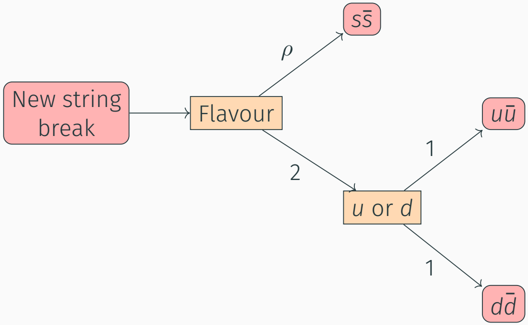


- Vast improvement, allowing 100s of variations!

Flavour reweighting: decision tree Monte Carlo (2312.xxxx)

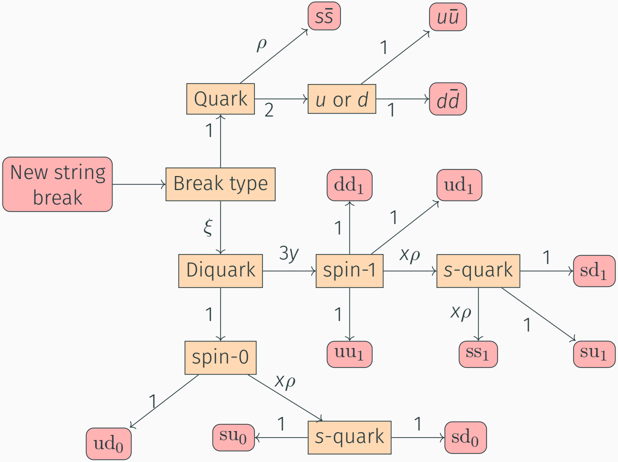
- Sample discrete flavour in string breakups, reweight to alternative reality with different input parameters.
- Weight calculable from string break history (simple only u, d and s. no baryons).

$$\mathcal{P}_{ns}(\rho) = \binom{N}{n} p^n (1-p)^{N-n} \Rightarrow w = \left(\frac{p}{p'}\right)^n (1-p')^{n-N}(1-p)^{N-n}$$



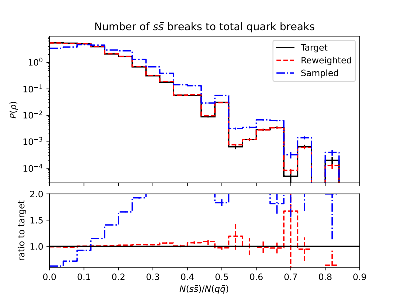
Flavour reweighting: baryons complicate matters (2312.xxxx)

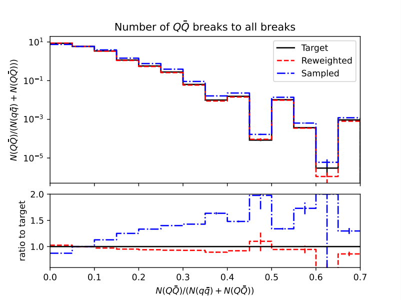
- Baryons much complicated: only simplest baryon model.
- Further accept/reject → SU(6) CGs.



Flavour reweighting: preliminary results I (2312.xxxx)

- Result at the level of string breaks, without accept/reject.
- Very rare configuration are often sought by experiment.

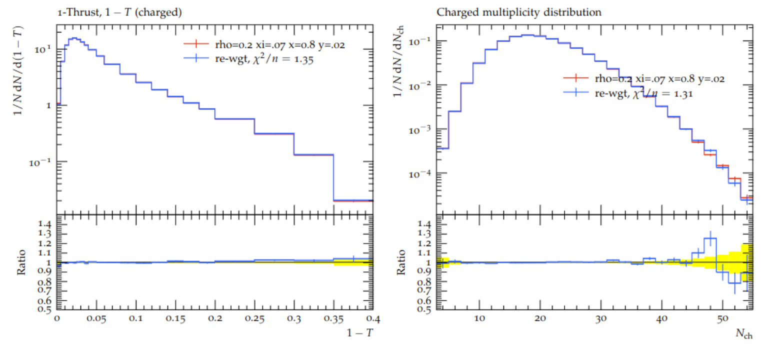




- Still only e^+e^-, pp is next step (junctions…).
- Take home: generate your rare hadron (or several) in almost every event, and reweight to correct cross section.

Flavour reweighting: preliminary results II (2312.xxxx)

- Results at final particle level, including accept/reject.
- Reweighting from defaults to altered values of ρ, ξ, x and y.



- Method works. Being implemented with normal HepMC weights. Publication in pipeline.

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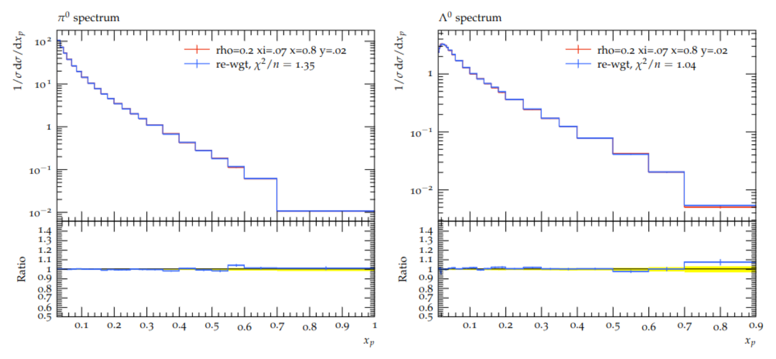

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Conclusion and outlook

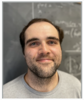
- Presented way of reweighting hadronization simulation, kinematics and flavour.
- On one hand: a technical improvement, allowing you to simulate quicker.
- On the other hand: a new way of thinking hadronization simulation.
- Reweightable techniques are apparently ubiquitous.
- Longer term: reweight everything, make tuning easy, perhaps per measurement.
- Even longer term: differentiable hadronization algorithm, use for model exclusion or Bayesian inference.
- Extremely long term: invertible models?

Thank you for your attention!

MLhad: Machine Learning Hadronization

C. Bierlich

P. Ilten



T. Menzo

S. Mrenna

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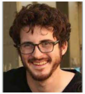

M. Szewc

M. Wilkinson

A. Youssef

J. Zupan

- Use ML for data driven hadronization description.
- Improve understanding of hadronization using ML methods.