Jet Matching
at Hadron Colliders

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Why jet matching?

- Many (all) interesting New Physics signals at hadron colliders include hadronic jets (from decay or recoil)
- All Standard Model backgrounds to multijet-processes (except top) have the jets coming from QCD radiation

→ Proper simulation of QCD radiation mandatory
Why jet matching?

- All SM backgrounds (by parton shower MC)
- Just Z+4 jets background (by matrix element MC)
- Same SUSY signal, after missing $E_T$ - and 4 jet-cuts
Why jet matching?

Parton shower Monte Carlo generators:
- Simulate QCD radiation in the soft-collinear limits
- Successive emissions through Markov chain evolution – unlimited number of emissions
- Highly tunable to fit data, but extrapolation dangerous away from soft-collinear limits

Matrix Element generators:
- Use the full matrix element of given jet multiplicity
- Reliable description far from soft-collinear limits
- Diverges in the soft and collinear limits
Why jet matching?

How produce an inclusive background sample?

- Need reliable simultaneous description of multiple jet multiplicities
- Need to allow using different cuts to optimize discovery of different signals

Criteria:

- No overcounting or undercounting of radiation
- Reproduce the inclusive cross section
- Smooth distributions in all kinematical observables
Why jet matching?

Double-counting between multiplicity samples

- 1-parton sample (no hard PS radiation)
- 2-parton sample (no hard PS radiation)
- 1-parton sample + hard PS radiation
Why jet matching?

Reglarization of matrix element divergence

Matrix element

Parton shower

Desired curve

$2^{nd}$ QCD radiation jet in top pair production at the LHC
LO jet matching techniques
The one-sentence “slogan” version

- **MLM matching - AlpGen, MadGraph**
  - Reject unmatched events after shower

- **CKKW matching - Sherpa**
  - Analytic NLL Sudakovs + vetoed showers

- **CKKW-Lönnblad matching - Ariadne**
  - Staged shower rejection (for each emission)

- **Shower reweighting - Geneva, Vincia**
  - Correct shower splittings with matrix element

For comparison, see arXiv:0706.2569
LO jet matching techniques

Pros and cons - my one-sentence slogan version

➢ MLM matching - AlpGen, MadGraph
  + Works for any shower with minimal modifications
  – Low efficiency, theoretically not (perfectly) well-controlled

➢ CKKW matching - Sherpa
  + No loss of events, theoretically well-controlled
  – Complicated shower treatment, matching unclear

➢ CKKW-Lönnblad matching - Ariadne
  + Perfect matching to shower, theoretically well-controlled
  – Low efficiency, complicated shower treatment

➢ Shower reweighting - Geneva, Vincia
  + Elegant and efficient, theoretically well-controlled
  – All new showers, still only final-state
MLM matching


Algorithm (in a nutshell):

1) Generate ME event with phase space cut $Q^{ME}$

2) Reweight $\alpha_s$ using scales for emissions in “shower history”  
   corresponding to event (e.g., using $k_T$-clustering)

3) Shower event with starting scale $= \mu_F = M_T$

4) Cluster shower emissions (before hadronization, using  
   “hook” in shower MC) to jets using $Q^{jet} > Q^{ME}$. Keep event if  
   each jet matches to one parton in the ME event
   - If highest parton multiplicity, allow extra jets < softest ME parton
MLM matching

$Q^{\text{match}} = 10 \text{ GeV}$

$Q^{\text{match}} = 30 \text{ GeV}$

$\log(\text{Jet resolution scale for } 1 \rightarrow 2 \text{ radiated jets} \sim p_T(2^{\text{nd}} \text{ jet}))$

$W+\text{jets production at the Tevatron}$

$\text{MadEvent+Pythia (}k_T\text{-jet MLM scheme)}$
CKKW matching

Catani, Krauss, Kuhn, Webber [hep-ph/0109231]
Krauss [hep-ph/0205283]

Prerequisite:

The inner workings of a parton shower

- The Sudakov form factor $\Delta(Q_1, Q_2) = P(\text{no QCD emission between } Q_1 \text{ and } Q_2) = \exp \left\{ - \int_{Q_1^2}^{Q_2^2} \frac{dq^2}{q^2} \frac{\alpha_s(q^2)}{2\pi} \int \frac{dz}{z} P_{ij}(z) \right\}$

- Parton shower starts from starting scale $\sim \mu_F$, picks emission scale based on $P(\text{emission at scale } Q)$

$$\frac{d}{dQ^2} (1 - \Delta) = \frac{\alpha_s(q^2)}{2\pi q^2} \int \frac{dz}{z} P_{ij}(z) \times \Delta(Q_1, Q)$$

For initial state

$$\frac{f_i(x_i/z, q^2)}{f_j(x_i, 2)}$$
CKKW matching

Probability for particular parton configuration after shower:

\[
\Delta_q^{IS}(d_2, d_3) \frac{\alpha_s(d_2^2)}{2\pi d_2^2} P_{qq}(z_2) \frac{x'_1 f(x'_1, d_2^2)}{x_1 f(x_1, d_2^2)}
\times \Delta_q^{IS}(d_{ini}, d_2) \Delta_q^{IS}(d_{ini}, d_3) \Delta_g^{FS}(d_1, d_2)
\times \frac{\alpha_s(d_1^2)}{2\pi d_1^2} P_{qg}(z_1) \times \Delta_q^{FS}(d_{ini}, d_1)^2
\times d\sigma_{2\to 1} f_q(x_1, d_3) f_{\bar{q}}(x_2, d_3)
\]

Red terms should be replaced by 2 → 3 matrix element

⇒ To get improved shower description, need

ME + \alpha_s reweighting + PDF reweighting + Sudakovs
CKKW matching

- All reweightings done in Matrix Element generator
- Next: Run shower to get emissions below $Q^{\text{match}}$
- If:
  - ME cutoff variable & Sudakov evolution variable identical to shower evolution variable
  - Shower is Markovian, i.e., gives the same result if started, stopped and restarted as if run the whole way

Then: Just start the shower at $Q^{\text{match}}$

- Otherwise: Use vetoed showers
CKKW matching

Vetoed showers

If matrix element cut is not aligned with shower evolution variable

1) Shower events, starting from central scale $\sim \mu_F$

2) If an emission is generated, check if it has $Q < Q^{\text{match}}$

3) If it does, keep it. Otherwise, ignore the emission and continue shower
CKKW matching

Differential jet rates in $W+\text{jets}$ at the Tevatron by Sherpa

$\log(\text{Jet resolution scale for } 0 \rightarrow 1 \text{ radiated jets} \sim p_T(1^{\text{st}} \text{ jet}))$

dotted: $Q^{\text{match}} = 30 \text{ GeV}$

[Talk by S. Schumann, 2004]
CKKW matching

- Results good (clearly at NLL accuracy), but matching to shower not perfect (Sudakovs differ)

- Solutions:
  1) Move to Lönnblad-inspired scheme, using shower to calculate Sudakovs through successive rejection
     - New Sherpa, see arXiv:0903.1219
  2) Use identical Sudakovs as in shower + fully Markovian shower
     - MadGraph/MadEvent + Pythia 6.4/8 (in progress)
MadGraph + Pythia (CKKW)

With perfect matching to shower – no dependence on matching scale (in shower region of validity)

Differential jet rates in W+jets at the LHC by MG/ME+Pythia

WORK IN PROGRESS

\( Q_{\text{match}} = 10, 20, 30 \)

Only ISR \( \log(\sim p_T(1^{\text{st}} \text{jet})) \)

ISR+FSR \( \log(\sim p_T(2^{\text{nd}} \text{jet})) \)
MadGraph + Pythia (CKKW)

Advantages:

- No loss of events in matching (factor ~3-5 gain)
- No special shower interface (just run the shower!)
- Full theoretical control
- “Difficult” processes (where I do not trust shower + MLM matching to give good Sudakov description)
  - Processes with b-quarks (pp → H±/±tb, pp → Hbb̅)
  - Processes with colorless t-channel exchange (WBF, t-channel single top)
- Allows for efficient phase space integration (poles regulated)
Matching in New Physics production

J.A., de Visscher, Maltoni [arXiv:0810.5350]

- We know that matching of ME+PS is vital for jet production in SM backgrounds
- But is it relevant for heavy BSM particle production?
  - Very hard jets from decays
  - Parton showers expected to be more accurate for larger masses
- Using gluino and squark production as example
- Turns out there are many cases where matching is necessary for precise description!
Double counting

Special difficulty in SUSY matching – double counting between squark and gluino production

Example: \(\tilde{q}\tilde{q}jj\)
Double counting

Special difficulty in SUSY matching – double counting between squark and gluino production

Example: $\tilde{q}\tilde{q}jj$

Double-counted with on-shell gluino prod with $\tilde{g} \to \tilde{d}_R + q$
Double counting

- Solved by keeping track of on-shell resonances in the production event files
  - Double-check – perform generation without resonant diagrams (gauge-inv. only in NWA)
    → Automatized (specify forbidden s-channel by $)
    → Excellent agreement
Shower parameter dependence

• Shower “tweakable”
  – Strength for fitting data (after-the-fact)
  – Weakness for predictivity

• Most important parameters used here:
  – Type of shower ($Q^2$ or $p_T$-ordered)
  – Shower starting scale
    • Factorization scale (mass of produced particle) - “wimpy”
    • Total energy of collider (14 TeV) - “power”

• Wide range of predictions from shower
Shower parameter dependence

QCD radiation for different Pythia shower params

\[
\log(\text{Jet resolution scale for } 1 \rightarrow 2 \text{ radiated jets}) \text{ (GeV)}
\]

600 GeV gluino pair production at the LHC
Shower parameter dependence

QCD radiation after matching with MG/ME

\[ \log(\text{Jet resolution scale for } 1 \rightarrow 2 \text{ radiated jets}) \text{ (GeV)} \]

600 GeV gluino pair production at the LHC
Shower parameter dependence

QCD radiation after matching with MG/ME

\[ \log(\text{Jet resolution scale for } 1 \rightarrow 2 \text{ radiated jets}) \text{ (GeV)} \]

Predictive \rightarrow \text{can now analyze QCD radiation}
Dependence on the initial state: gg, qq

600 GeV gluino vs. squark squark production at LHC

No single shower tune for all initial states!
Dependence on SUSY particle mass

Gluino production at LHC

300 GeV  600 GeV  1200 GeV

Well-determined dependence of radiation on mass
Jet counting in gluino decay

600 GeV gluino pair production

3-body g decay
(squarks heavy)

$M_g - M_q = 50$ GeV

$\Sigma p_T(2$ hardest jets) $\Sigma p_T(3$ hardest jets) $\Sigma p_T(4$ hardest jets)

1 jet from ISR

All decay jets
Example


- Example: Gluinos that decay to qq+LSP with free ratio of gluino/LSP mass
- Special difficulty when decay products nearly mass-degenerate with produced particle
  - No (small) missing transverse energy in decay
Example

• Example: Gluinos that decay to qq+LSP with free ratio of gluino/LSP mass

• Special difficulty when decay products nearly mass-degenerate with produced particle
  - No (small) missing transverse energy in decay
  - Need recoil against ISR jet!
\(M_g = 150 \text{ GeV}\)

\(M_B = 40 \text{ GeV}\)

\(M_g = 150 \text{ GeV}\)

\(M_B = 130 \text{ GeV}\)

\(p_T(j1)\) at the Tevatron, after 2-jet and missing \(E_T\) cuts
Conclusions

- LO jet matching techniques are a powerful complement to matched NLO simulations
- Several approaches available, with different strengths and weaknesses
- Matching important also for simulation of new physics signals
- Continuous development / improvement
  - Sherpa (cf. arXiv:0903.1219)
  - MadGraph/MadEvent + Pythia (in progress)