Karlsruhe Institute of Technology

Massive Dipole Shower in Matchbox Herwig++

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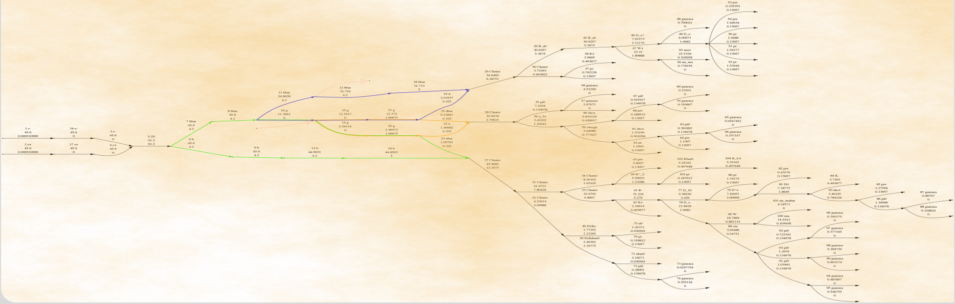
INSTITUTE FOR THEORETICAL PHYSICS



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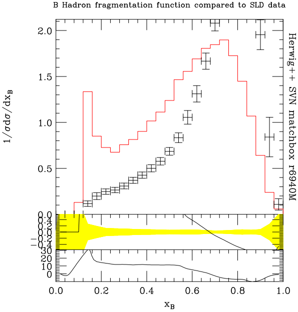
Motivation

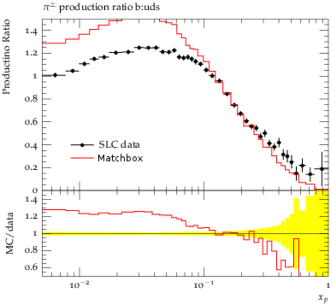
Herwig++'s Matchbox module

- written by Simon Plätzer
- extension to Herwig++ multi-purpose MC event generator
- introduces a new Catani-Seymour dipole shower ($2 \to 3$ splittings instead of Herwig++'s $1 \to 2$ splittings)
- goal: automated NLO matching
- to be published in Herwig++'s next scheduled release
- generally good description of experimental data
- problems with observables concerning heavy quarks (treats all partons as if massless)

Motivation

$e^+e^- \mapsto$ *jets* with Matchbox vs data





⇒ add modifications which improve to incorporate finite parton masses

Catani-Seymour Subtraction Formalism

- We start with an NLO cross section

$$\sigma = \sigma^{LO} + \sigma^{NLO} = \int_m d\sigma^B + \int_m d\sigma^V + \int_{m+1} d\sigma^R$$

- real & virtual contributions are seperately divergent
  $\Rightarrow$ no straightforward numeric implementation
- Idea: introduce auxiliary cross section $d\sigma^A$ as local counterterm for $d\sigma^R$
  $\Rightarrow$

$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R \right)_{\epsilon=0} - \left(d\sigma^A \right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

Catani-Seymour Subtraction Formalism

- factorization in soft & collinear limits

$$d\sigma^R = d\sigma^B \cdot \text{(process-independent factor)}$$

- introduce “dipoles”

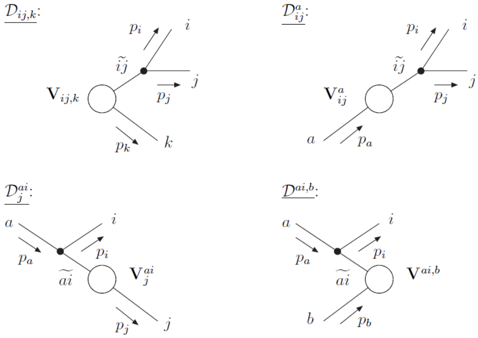
$$d\sigma^A = \sum_{dipoles} d\sigma^B \otimes dV_{dipole}$$

- furthermore:

$$\int_{m+1} d\sigma^A = \int_m \sum_{dipoles} d\sigma^B \otimes \int_1 dV_{dipole} \equiv \int_m \left[d\sigma^B \otimes I \right]$$

$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R \right)_{\epsilon=0} - \left(\sum_{dipoles} d\sigma^B \otimes dV_{dipole} \right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + d\sigma^B \otimes I \right]_{\epsilon=0}$$

Catani-Seymour Subtraction Formalism



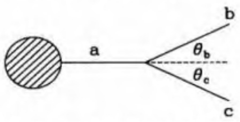
$$\mathcal{D}_{ij,k}(p_1, ..., p_{m+1}) =$$
$$-\frac{1}{(p_i + p_j)^2 - m_{ij}^2}\ {}_m\langle ..., \tilde{ij}, ..., \tilde{k}, ...|\frac{T_k \cdot T_{ij}}{T_{ij}^2} V_{ij,k}|..., \tilde{ij}, ..., \tilde{k}, ...\rangle_m$$

Parton Showers

- fixed-order QCD calculations are enhanced by higher orders in the following phasespace regions (leading logarithms)
  - soft emission
  - collinear splitting
- cross section $d\sigma_{n+1}$ approximated by virtue of factorization theorems:

$$d\sigma_{n+1} = d\sigma_n d\mathcal{P}_{ba}$$

- $d\mathcal{P}_{ba}$: splitting probability



kinematic variables: $z = E_b/E_a$, evolution variable (e.g. virtuality)

- angular ordering assures correct leading log contribution

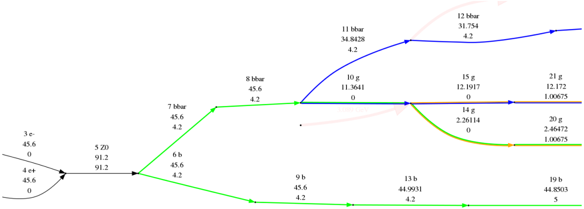
Dipole Shower: Introduction

- based on Catani-Seymour dipoles
- $2 \to 3$ splittings allow on-shell partons at each step
- splitting kinematics of massless partons $(\tilde{p}_{ij}, \tilde{p}_k) \to (p_i, p_j, p_k)$

$$p_i = z\tilde{p}_{ij} + \frac{p_\perp^2}{zs}\tilde{p}_k + k_\perp$$
$$p_j = (1-z)\tilde{p}_{ij} + \frac{p_\perp^2}{(1-z)s}\tilde{p}_k - k_\perp$$
$$p_k = (1-y)\tilde{p}_k$$

- $z = \frac{p_i p_k}{(p_i+p_j)p_k}, \quad y = \frac{p_i p_j}{p_i p_j + p_i p_k + p_j p_k}$
- $p_\perp$ ordering guiding the evolution

Dipole Shower



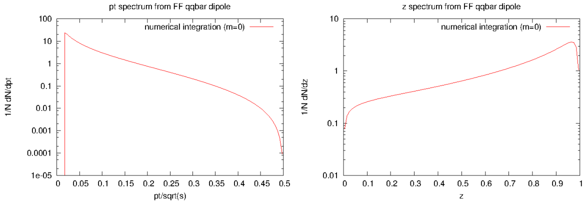
- want to calculate $p_\perp$ spectrum
  i.e. probability of evolving from a hard scale $p_\perp^h$ to a scale $p_\perp$ without splitting and split at scale $p_\perp$
- have: probability of splitting in $[p_\perp^2, p_\perp^2 - dp_\perp^2]$: $d\mathcal{P}_{\tilde{ij}\to i,j;k}$
- need probability of unresolved splitting $\Delta_{\tilde{ij}\to i,j;k}(p_\perp^{h2}, p_\perp^2)$

Dipole Shower

- unitarity leads to probability for unresolved splitting in $[p_\perp^2, p_\perp^2 - dp_\perp^2]$: $\quad 1 - \sum_{(i,j)} d\mathcal{P}_{\tilde{ij}\to i,j;k}$
- $\to$ Sudakov form factor (no-splitting prob. between $p_\perp^{h2}$ and $p_\perp^2$)

$$\Delta_{\tilde{ij}\to i,j;k}(p_\perp^{h2}, p_\perp^2) = \exp\left[-\sum_{(i,j)} \int_{p_\perp^2}^{p_\perp^{h2}} \frac{d\bar{p}_\perp^2}{\bar{p}_\perp^2} \int_{z_-(\bar{p}_\perp^2)}^{z_+(\bar{p}_\perp^2)} dz \frac{\alpha_s}{2\pi} P_{\tilde{ij}\to i,j;k}(\bar{p}_\perp^2, z)\right]$$

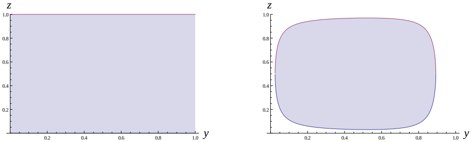
- $p_\perp$, z spectra of a (FF) $q\bar{q}$ dipole



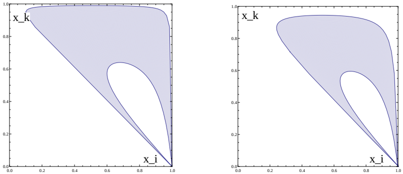
Dipole Shower: Phasespace

- impact of parton masses on splitting phasespace

(y, z) phasespace for massless and massive partons

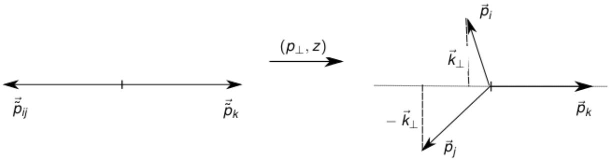


phasespace in Dalitz variables (x_i, x_j) for massless and massive partons



Dipole Shower: massive kinematics

- splitting kinematics are described by either $(p_\perp, z)$ or (y, z)
- the algorithm is most efficient if first a value of $p_\perp$ in $[p_\perp^h, \mu_{IR}]$ is created $\rightarrow (p_\perp, z)$



- problem: Sudakov decomposition becomes very unwieldy
- instead: it is straightforward to determine 4-momentum components explicitly as functions of Lorentz-invariants y and z
- $p_\perp$ can be read off the momentum vector
  BUT: no applicable inverse mapping $(p_\perp, z) \mapsto (y, z)$

Dipole Shower: massive kinematics

- in the quasi-collinear limit ($m_i \mapsto \lambda m_i, \quad p_\perp \mapsto \lambda p_\perp$ with $\lambda \mapsto 0$) a Sudakov decomposition analoguous to massless case can be given

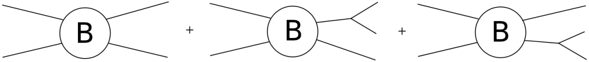
$$p_i = zp + \frac{p_\perp^2 - z^2 m_{ij}^2 + m_i^2}{z} \frac{n}{2p \cdot n} + k_\perp$$

$$p_j = (1-z)p + \frac{p_\perp^2 - (1-z)^2 m_{ij}^2 + m_j^2}{1-z} \frac{n}{2p \cdot n} - k_\perp$$

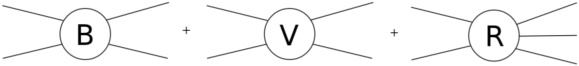
- $\Rightarrow$ simple relation between $(y, z) \leftrightarrow (p_\perp, z)$ (in this limit), which will be used
- physical $p_\perp$ does not coincide with $p_\perp(y, z)$ outside this limit
- no influence on shower dynamics since all relations hold in the quasi-collinear limit
- shower ordering in $p_\perp^{quasi-coll.}$

NLO Matching: Introduction

- have constructed shower which predicts to $\mathcal{O}(\alpha_s)$



- also know NLO matrix element



- question: how can we achieve the shower predicts the correct NLO matrix element?

NLO Matching

NLO prediction for an observable O

$$\langle O^{NLO} \rangle = \int_m dx B(x) O(x) + \alpha_s \int_{m+1} dxdy \frac{R(x,y)}{y} O(x,y)$$
$$+ \alpha_s \int_m dx V(x) O(x)$$
$$\downarrow \text{CS}$$
$$= \int_m dx B(x) O(x) + \alpha_s \int_{m+1} dxdy \frac{R(x,y)O(x,y) - A(x,y)O(x)}{y}$$
$$+ \alpha_s \int_m dx \left[V(x) + \int_1 dy \frac{A(x,y)}{y^{1-\epsilon}} \right] O(x)$$

NLO Matching

$\mathcal{O}(\alpha_s)$ parton shower prediction starting off Born process

$$\langle O \rangle_{PS} = \int_{m+1} dxdyB(x) \left[\delta(y)\Delta(x) + \theta(y-\mu)\alpha_s \frac{P(x,y)}{y} \Delta(x) \right] O(x,y)$$

with Sudakov form factor

$\Delta(x) = e^{-\alpha_s \int_\mu^1 dy' \frac{P(x,y')}{y'}} = 1 - \alpha_s \int_\mu^1 dy' \frac{P(x,y')}{y'} + \mathcal{O}(\alpha_s^2)$

this yields

$$\langle O \rangle_{PS} = \int_m dxB(x)O(x) + \alpha_s \int_{m+1} dxdy \frac{P(x,y)}{y} \left[O(x,y) - O(x) \right] B(x) + \mathcal{O}(\alpha_s^2)$$

NLO Matching

$$\langle O^{NLO}\rangle = \int_m dxB(x)O(x) + \alpha_s \int_{m+1} dxdy\, \frac{R(x,y)O(x,y) - A(x,y)O(x)}{y} + \alpha_s \int_m dx \left[V(x) + \int_1 dy\, \frac{A(x,y)}{y^{1-\epsilon}} \right] O(x)$$

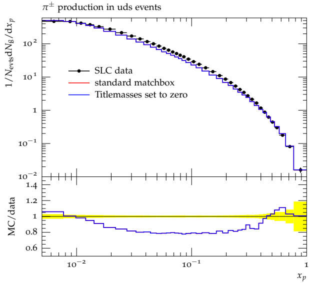
$$\langle O\rangle_{PS} = \int_{m+1} dxB(x)O(x) + \alpha_s \int_{m+1} dxdy\, \frac{P(x,y)}{y} \left[O(x,y) - O(x)\right] B(x) + \mathcal{O}(\alpha_s^2)$$

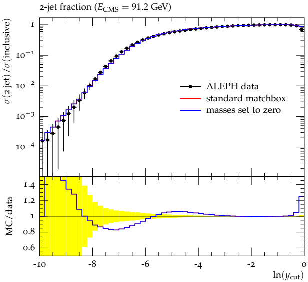
$\Rightarrow$ double counting of $\mathcal{O}(\alpha_s)$ contribution

$$\begin{aligned}
\langle O\rangle^{NLO}_{matched} = & \int_m dxB(x)O(x) \\
& + \alpha_s \int_m dx \left[V(x) + \int_1 dyA(x,y)y^{\epsilon-1} \right] O(x) \\
& + \alpha_s \int_{m+1} dxdy\, \frac{P(x,y)B(x) - A(x,y)}{y} O(x) \\
& + \alpha_s \int_{m+1} dxdy\, \frac{R(x,y) - P(x,y)B(x)}{y} O(x,y)
\end{aligned}$$

Simulation Results 1

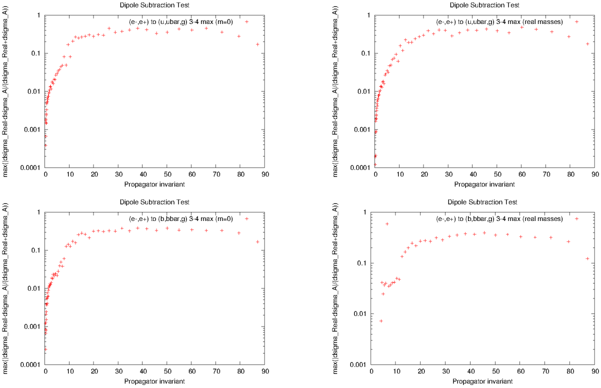
- Consistency check 1
  - set masses to zero
  - compare to standard matchbox





Simulation Results 1

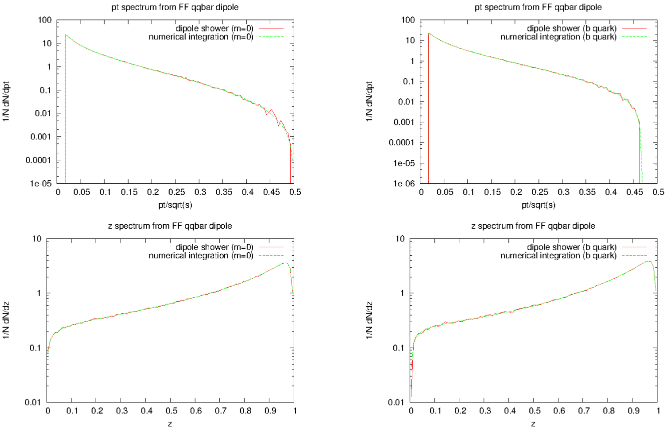
- Consistency check 2
  - check subtraction



massless partons massive partons

Simulation Results 2

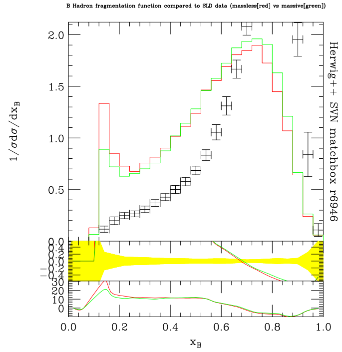
- Compare $p_\perp$, z spectra of the first emission to numerical calculation

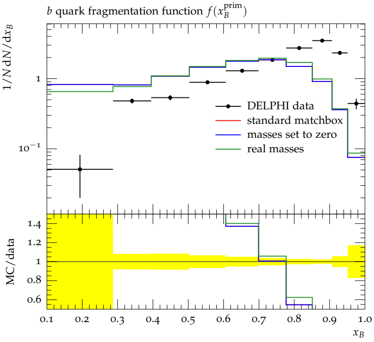


Simulation Results 2

Compare new massive shower to standard dipole shower

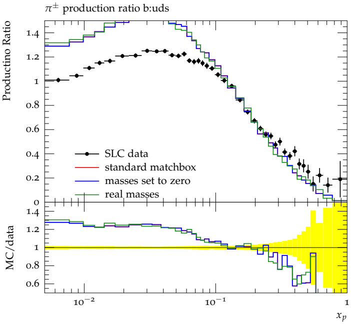
- b quark fragmentation

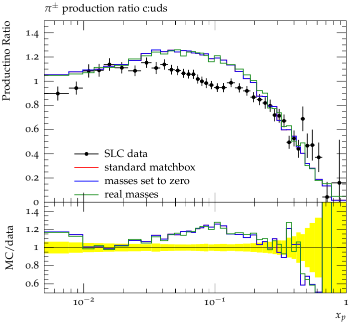




Simulation Results 2

- identified particle spectra

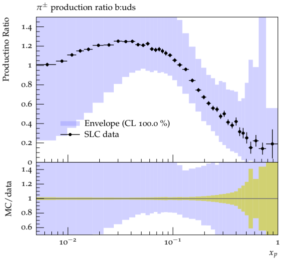


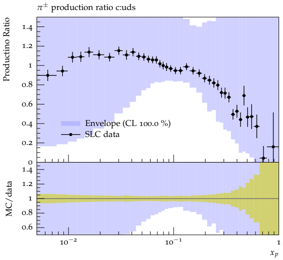


$\Rightarrow$ parameter tuning is required

Outlook: Tuning

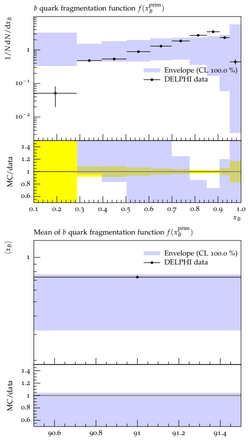
- Tuning: fitting free parameters (cutoffs, hadronization parameters etc.) to data
- without tuning the impact of the massive shower is limited
- new parameters for heavy quarks are expected to reduce tension between event shapes and b fragmentation
- a first test run with different parameter sets seems promising:
  - envelope plots for $\pi^{\pm}$ production ratios

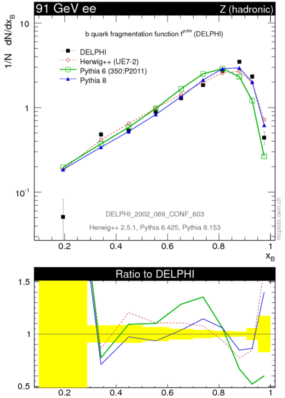




Outlook: Tuning

- b fragmentation fuction: dipole shower (envelope plots, l.h.s.) vs Herwig++ with standard shower (several different tunes, r.h.s)





Outlook

Done so far

- Implementation of massive final-final (FF) shower
- Implementation of NLO $e^+e^- \mapsto q\bar{q}$ matrix element and matching ingredients
- Validation of shower & matching
- Investigation of the impact on some observables

Still to be done

- Tuning (in progress)
- Implement FI,IF,II dipole shower (DIS / hadron colliders)

Thank you for your attention!