3rd MCNet Meeting / Göstafest, Lund, January 2008

Time-like Showers and Matching with Antennae

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In collaboration with R. Frederix, W. Giele, D. Kosower, T. Sjöstrand

Parton Showers

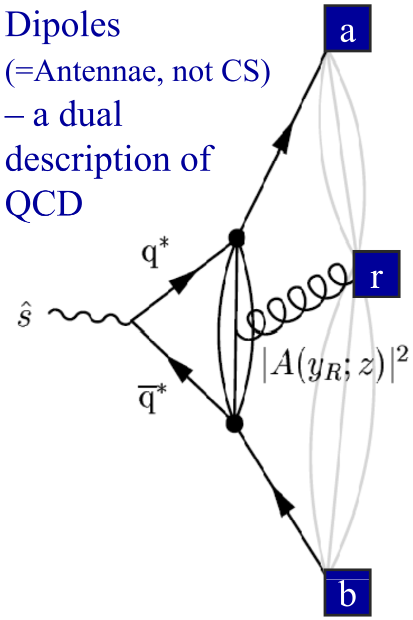
- The final answer depends on:
  - The choice of evolution variable
  - The splitting functions (finite/subleading terms not fixed)
  - The phase space map ($d\Phi_{n+1}/d\Phi_n$)
  - The renormalization scheme (argument of α_s)
  - The infrared cutoff contour (hadronization cutoff)
- Step 1, Quantify uncertainty: vary all of these (within reasonable limits)
- Step 2, Systematically improve: Understand the importance of each and how it is canceled by
  - Matching to fixed order matrix elements
  - Higher logarithms, subleading color, etc, are included
- Step 3, Write a generator: Make the above explicit (while still tractable) in a Markov Chain context → matched parton shower MC algorithm

Gustafson, PLB175(1986)453; Lönnblad (ARIADNE), CPC71(1992)15.
Azimov, Dokshitzer, Khoze, Troyan, PLB165B(1985)147
Kosower PRD57(1998)5410; Campbell,Cullen,Glover EPJC9(1999)245

► Based on Dipole-Antennae

- Shower off color-connected pairs of partons
- Plug-in to PYTHIA 8.1 (C++)

Dipoles (=Antennae, not CS) – a dual description of QCD

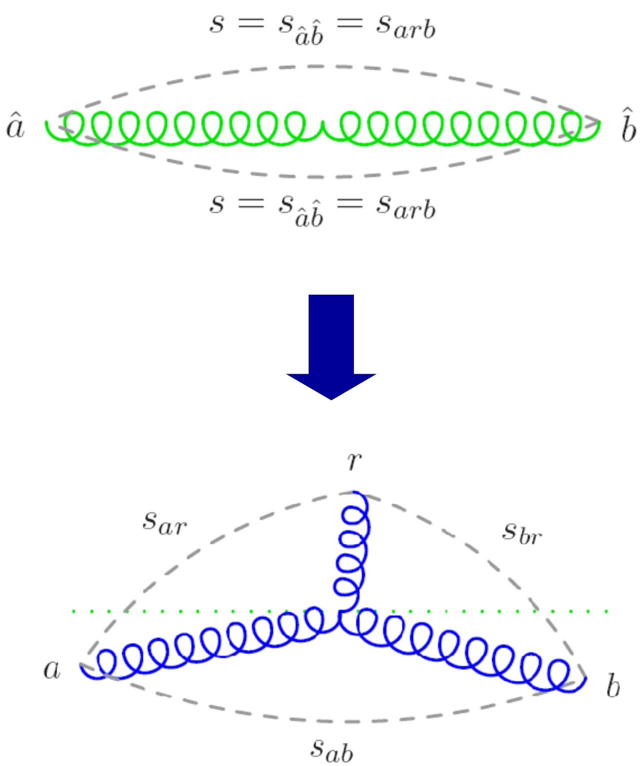


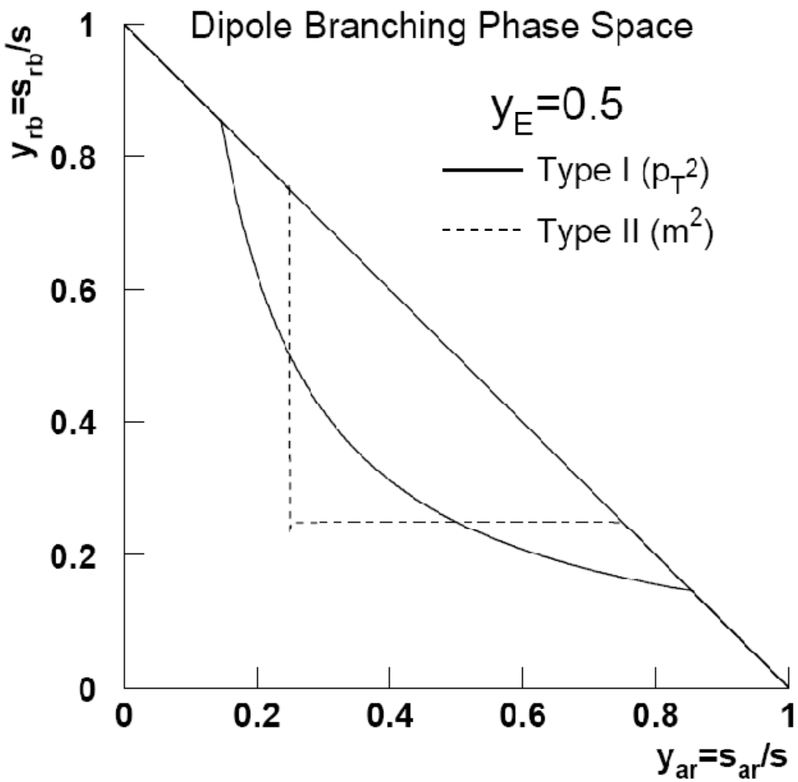
► So far: Giele, Kosower, PS : hep-ph/0707.3652 + Les Houches 2007

- Time-like QCD cascades (with massless quarks)
- 2 different shower evolution variables:
  - pT-ordering (= ARIADNE ~ PYTHIA 8)
  - Dipole-mass-ordering (~ Thrust ≠ PYTHIA 6, SHERPA)
- For each: an infinite family of antenna functions
  - Laurent series in branching invariants with arbitrary finite terms
- Shower cutoff contour: independent of evolution variable
  → IR factorization "universal"
- Several different choices for α_s (evolution scale, p_T, mother antenna mass, 2-loop, …)
- Phase space mappings: 2 different choices implemented
  - Antenna-like (ARIADNE angle) or Parton-shower-like: Emitter + longitudinal Recoiler

Dipole-Antenna Showers

► Dipole branching and phase space





(➔ Most of this talk, including matching by antenna subtraction, should be applicable to ARIADNE as well)

Giele, Kosower, PS : hep-ph/0707.3652

Example: Z decays

► VINCIA and PYTHIA8 (using identical settings to the max extent possible)

$\alpha_s(p_T)$,

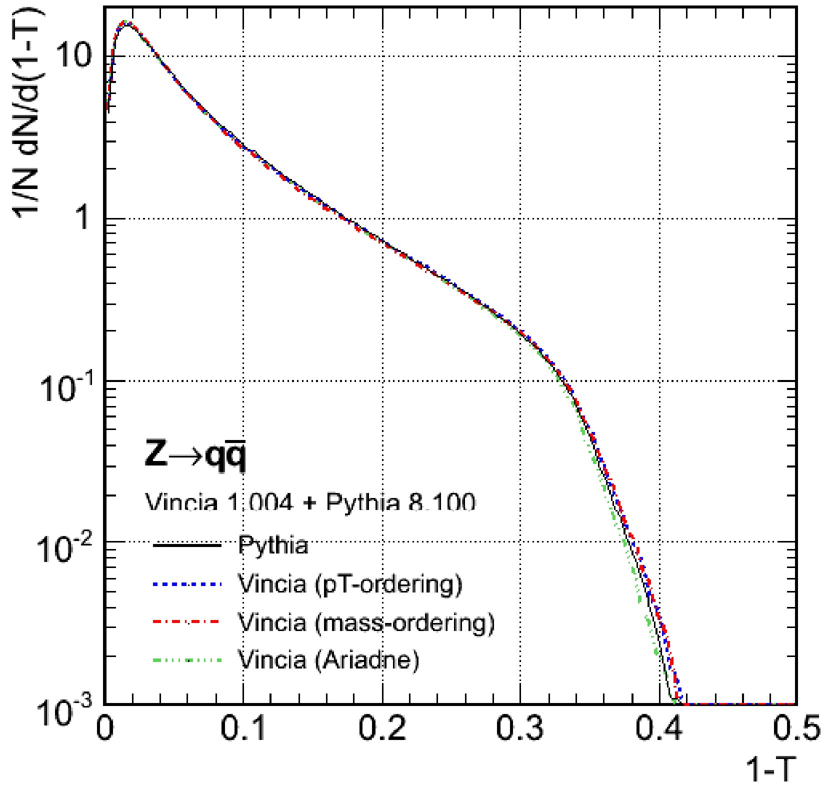
$p_{Thad} = 0.5$ GeV

$\alpha_s(m_Z) = 0.137$

$N_f = 2$

Note: the default Vincia antenna functions reproduce the Z→3 parton matrix element;

Pythia8 includes matching to Z→3



Frederix, Giele, Kosower, PS : Les Houches Proc., in preparation

Example: Z decays

- Why is the dependence on the evolution variable so small?
  - Conventional wisdom: evolution variable has huge effect
    - Cf. coherent vs non-coherent parton showers, mass-ordered vs p_T-ordered, etc.
- Dipole-Antenna showers resum radiation off *pairs* of partons
    - → interference between 2 partons included in radiation function
  - If radiation function = dipole formula → intrinsically coherent
    - → angular ordering there by construction Gustafson, PLB175(1986)453
  - Remaining dependence on evolution variable much milder than for conventional showers
- The main uncertainty in this case lies in the choice of radiation function away from the collinear and soft regions
  - → dipole-antenna showers under the hood …

Dipole-Antenna Functions

Giele, Kosower, PS : hep-ph/0707.3652

- Starting point: "GGG" antenna functions, e.g., gg→ggg:

Gehrmann-De Ridder, Gehrmann, Glover, JHEP 09 (2005) 056

$$f_3^0(p_a,p_r,p_b) = \frac{1}{s^{[i]}}\left[(1-y_{ar}-y_{rb})\left(\underbrace{\frac{2}{y_{ar}y_{rb}}}_{\text{"soft"}} + \underbrace{\frac{y_{ar}}{y_{rb}} + \frac{y_{rb}}{y_{ar}}}_{\text{"collinear"}}\right) + \frac{8}{3}\right]$$

$y_{ar} = s_{ar} / s_i$

s_i = invariant mass of i'th dipole-antenna

- Generalize to arbitrary Laurent series:

$$A(s_{ar},s_{rb}) = \frac{4\pi\alpha_s(\mu_R)N_C}{s_{arb}} \sum_{\alpha,\beta\geq -1} C_{\alpha\beta}\frac{s_{ar}^{\alpha}s_{rb}^{\beta}}{s_{arb}^{\alpha+\beta}}$$

Singular parts fixed, finite terms arbitrary

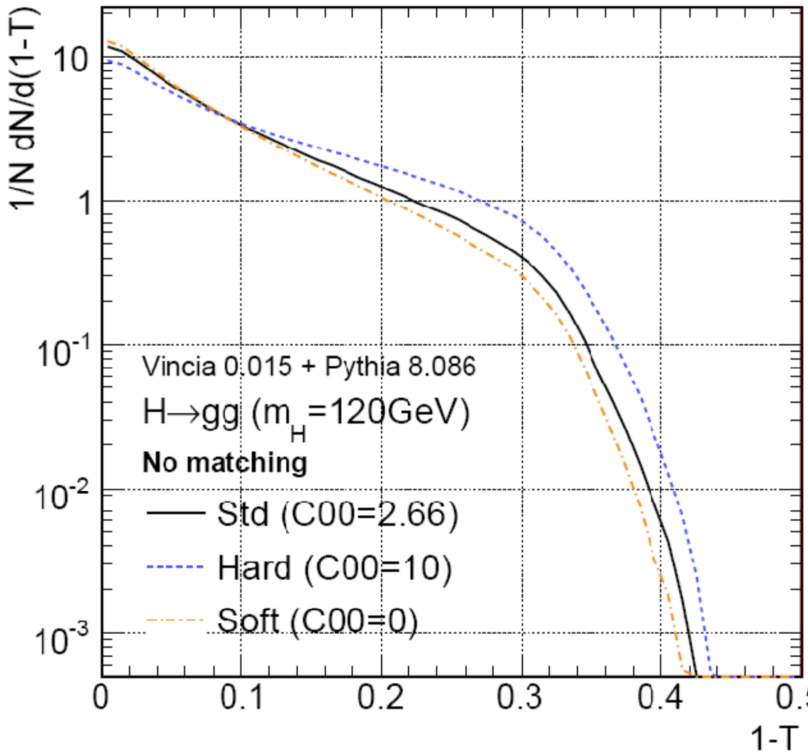
→ Can make shower systematically "softer" or "harder"

- Will see later how this variation is explicitly canceled by matching
- → quantification of uncertainty
- → quantification of improvement by matching

Quantifying Matching

► The unknown finite terms are a major source of uncertainty

- DGLAP has some, GGG have others, ARIADNE has yet others, etc…
- They are arbitrary (and in general process-dependent)



Giele, Kosower, PS : hep-ph/0707.3652

← Varying finite terms only

with

$\alpha_s(M_Z)$=0.137,
μ_R=1/4m_{dipole},
p_{Thad} = 0.5 GeV

Matching

$w_X : |M_X|^2$

S : Evolution operator

{p} : momenta

Pure Shower (all orders)

$$\left.\frac{d\sigma_X}{d\mathcal{O}}\right|_{PS} = \int d\Phi_X \, w_X \, S(\{p\}_X, \mathcal{O})$$

$$S(\{p\}_X, \mathcal{O}) = \underbrace{\delta\left(\mathcal{O} - \mathcal{O}(\{p\}_X)\right) \Delta(t_X, t_{\rm had})}_{X + 0 \text{ exclusive above } 1/t_{\rm had}}$$

$$+ \underbrace{\int_{t_X}^{t_{\rm had}} dt_{X+1} \sum_i \int \frac{d\Phi^{[i]}_{X+1}}{d\Phi_X} \delta(t_{X+1} - t^{[i]}(\{p\}_{X+1})) \Delta(t_X, t_{X+1}) A_i(\ldots) S(\{p\}_{X+1}, \mathcal{O})}_{X + 1 \text{ inclusive above } 1/t_{\rm had}}$$

← "X + nothing"

"X+something"

A: splitting function

Matched shower (including simultaneous tree- and 1-loop matching for any number of legs)

$$\left.\frac{d\sigma}{d\mathcal{O}}\right|_{MS} = \sum_{k=0}^{n} \int d\Phi_{X+k} \left(w^{(R)}_{X+k} + w^{(V)}_{X+k} \right) S(\{p\}_{X+k}, \mathcal{O})$$

Tree-level "real" matching term for X+k

Loop-level "virtual+unresolved" matching term for X+k

Giele, Kosower, PS : hep-ph/0707.3652

Tree-level matching to X+1

1. Expand parton shower to 1st order (real radiation term)

PS : $$\int d\Phi_X \, |M^{(0)}_{X+0}|^2 \int_{t_{X+0}}^{t_{\rm had}} dt_{X+1} \sum_i \int \frac{d\Phi^{[i]}_{X+1}}{d\Phi_X} \, \delta(t_{X+1} - t^{[i]}(\{p\}_{X+1})) A_i(\ldots) \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_{X+1})\right)$$

2. Matrix Element (Tree-level X+1 ; above $t_{\rm had}$)

ME : $$\int_{t<t_{\rm had}} d\Phi_{X+1} \, |M^{(0)}_{X+1}|^2 \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_{X+1})\right)$$

Inverse phase space map ~ clustering
$\{\hat{p}_i\}_X = \{\kappa_i^{-1}(\{p\}_{X+1})\}_X$

➔ Matching Term:

MT : $$w^{(R)}_{X+1} = |M^{(0)}_{X+1}|^2 \; - \sum_{i \in X \to X+1} A_i(\ldots) |M^{(0)}_{X+0}(\{\hat{p}_i\}_{X+0})|^2$$

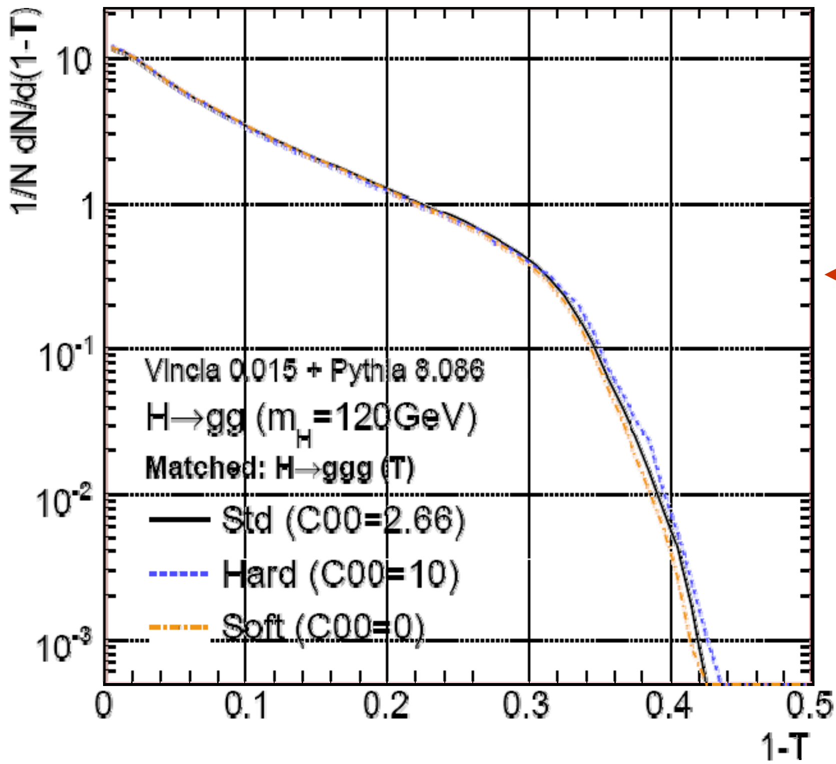
- → variations in finite terms (or dead regions) in A_i **canceled** (at this order)
- (If A too hard, correction can become negative → **negative weights**)

$$= \frac{8\pi\alpha_s(\mu_R) N_c}{M_H^2} \Big(8 - 3C_{00} - (C_{10} + C_{01}) - C_{11}\,(y_{12}y_{23} + y_{23}y_{31} + y_{31}y_{12}) + \cdots\Big) |M_2^{(0)}|^2$$

Giele, Kosower, PS : hep-ph/0707.3652

Quantifying Matching

- ► The unknown finite terms are a major source of uncertainty
  - DGLAP has some, GGG have others, ARIADNE has yet others, etc…
  - They are arbitrary (and in general process-dependent)



Varying finite terms only

with $\alpha_s(M_Z)$=0.137, μ_R=1/4m_{dipole}, p_{Thad} = 0.5 GeV

Giele, Kosower, PS : hep-ph/0707.3652

1-loop matching to X

- NLO "virtual term" from parton shower (= expanded Sudakov: exp=1 - …)

$$\text{PS} \quad : \quad -\int \mathrm{d}\Phi_X \, |M_X^{(0)}|^2 \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_X)\right) \int_{t_X}^{t_{\mathrm{had}}} \mathrm{d}t_{X+1} \sum_i \int \frac{\mathrm{d}\Phi_{X+1}^{[i]}}{\mathrm{d}\Phi_X} \delta(t_{X+1} - t^{[i]}(\{p\}_{X+1})) A_i(\ldots)$$

- Matrix Elements (unresolved real plus genuine virtual)

$$\text{ME} \quad : \quad \int_{t>t_{\mathrm{had}}} \mathrm{d}\Phi_{X+1} |M_{X+1}^{(0)}|^2 \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_{X+1})\right) + \int \mathrm{d}\Phi_X 2\,\mathrm{Re}[M_X^{(0)} M_X^{(1)*}] \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_X)\right)$$

- Matching condition same as before (almost):

$$\begin{aligned} \text{MT}: \quad w_X^{(V)} &= 2\,\mathrm{Re}[M_X^{(0)} M_X^{*(1)}] + |M_X^{(0)}|^2 \sum_i \int_{\mathrm{all}\, t} \frac{\mathrm{d}\Phi_{X+1}^{[i]}}{\mathrm{d}\Phi_X} A_i(\ldots) + \int_{t>t_{\mathrm{had}}} \mathrm{d}\Phi_{X+1} w_{X+1}^{(R)} \\ &= 2\,\mathrm{Re}[M_X^{(0)} M_X^{*(1)}] + |M_X^{(0)}|^2 \sum_i \int_{\mathrm{all}\, t} \frac{\mathrm{d}\Phi_{X+1}^{[i]}}{\mathrm{d}\Phi_X} A_i(\ldots) + \mathcal{O}(t_X/t_{\mathrm{had}}) \, , \end{aligned}$$

  - (This time, too small A → correction negative)

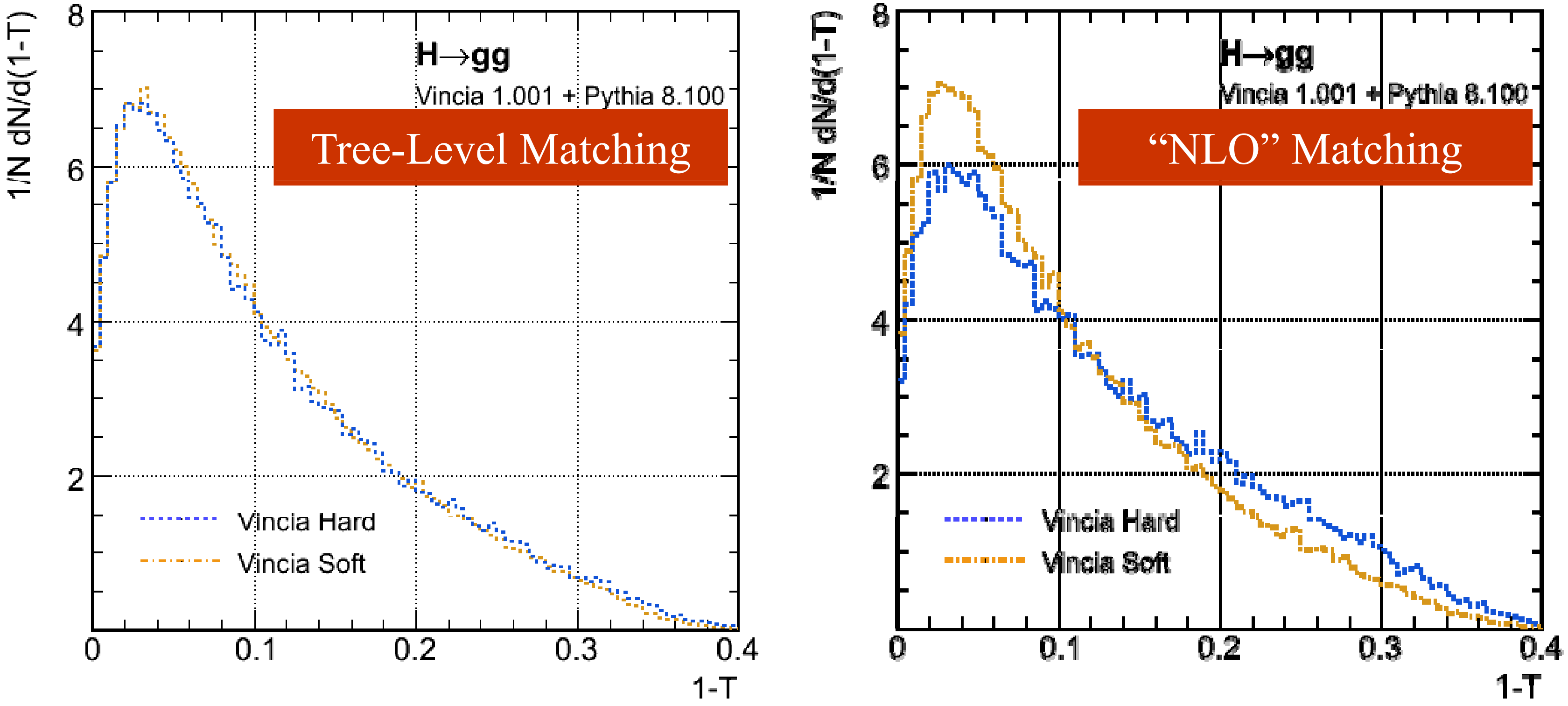
Tree-level matching just corresponds to using zero

- You can choose anything for A_i (different subtraction schemes) as long as you use the same one for the shower

Giele, Kosower, PS : hep-ph/0707.3652

Note about "NLO" matching

- Shower off virtual matching term ➔ unmatched $O(\alpha^2)$ contribution to 3-jet observables (only canceled by 1-loop 3-parton matching)
- While normalization is improved, most shapes are not



Using $\alpha_s(M_Z)$=0.137, μ_R=1/4m_{dipole}, p_{Thad} = 0.5 GeV

What happened?

- ► Brand new code, so bear in mind possibility of bugs
- ► Naïve conclusion: tree-level matching "better" than NLO?
  - No, first remember that the shapes we look at are not "NLO"
    - E.g., 1-T appears at O(α) below 1-T=2/3, and at O(α^2) above
    - An "NLO" thrust calculation would have to include *at least* 1-loop corrections to Z→3
  - So: both calculations are LO/LL from the point of view of 1-T
- ► What is the difference then?
  - Tree-level Z→3 is the same (LO)
  - The O(α) corrections to Z→3, however, are different
    - The first non-trivial corrections to the shape!
    - So there *should* be a large residual uncertainty → the 1-loop matching is "honest"
  - The real question: why did the tree-level matching not tell us?
    - I haven't completely understood it yet … but speculate it's to do with detailed balance
    - In tree-level matching, unitarity → Virtual = - Real → cancellations. Broken at 1 loop
    - + the tree-level curves had different normalizations (covering the shape uncertainty?)

What to do next?

- ► Further shower studies
  - Interplay between shower ambiguities and hadronization "tuning"
  - Shower+hadronization tuning in the presence of matching
- ► Go further with tree-level matching
  - Demonstrate it beyond first order (include H,Z → 4 partons)
  - Automated tree-level matching (automated subtractions)
- ► Go further with one-loop matching
  - Demonstrate it beyond first order (include 1-loop H,Z → 3 partons)
    - Should start to see genuine stabilization of shapes as well as normalizations
- ► Extend to the initial state
- ► Extend to massive particles
  - Massive antenna functions, phase space, and evolution

We're only a few people working part-time, so plenty of room for collaboration

Extra Material

Frederix, Giele, Kosower, PS : Les Houches Proc., in preparation

► Number of partons and number of quarks

- N_q shows interesting dependence on ordering variable

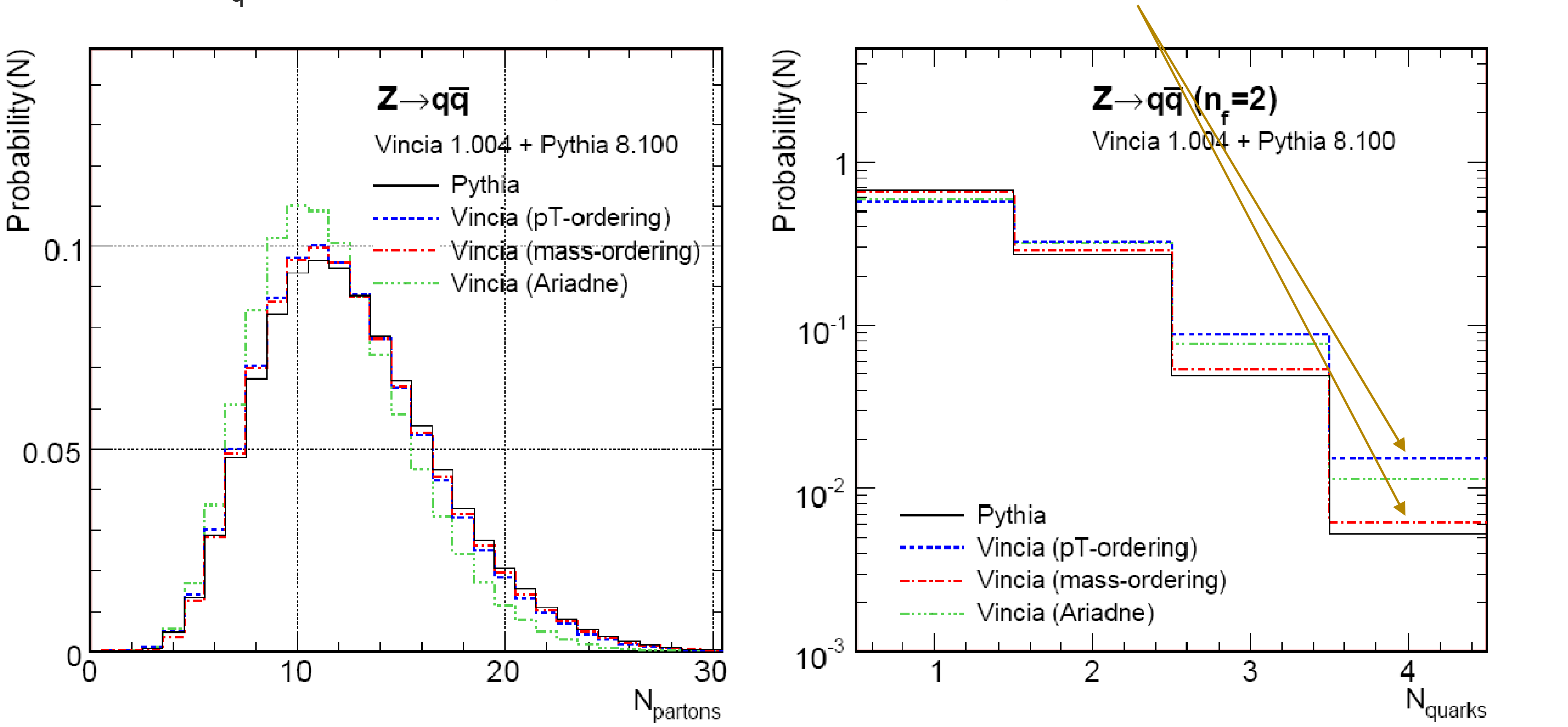


Fig. 3: Number of partons (left) and number of quarks (right) at shower termination, with 2 massless quark flavors.

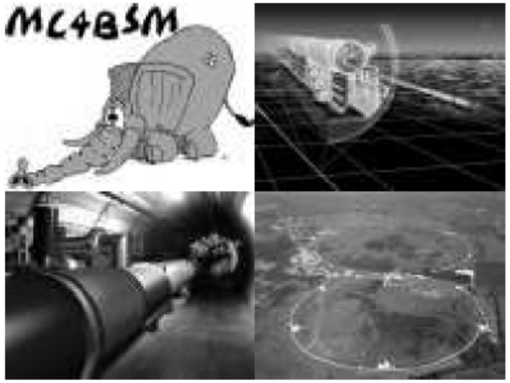
Comparison

$$A(s_{ar}, s_{rb}) = \frac{4\pi\alpha_s(\mu_R)N_C}{s_{arb}} \sum_{\alpha,\beta\geq -1} C_{\alpha\beta} \frac{s_{ar}^{\alpha} s_{rb}^{\beta}}{s_{arb}^{\alpha+\beta}}$$

	C_{-1-1}	C_{-10}	C_{0-1}	C_{-11}	C_{1-1}	C_{-12}	C_{2-1}	C_{00}	C_{10}	C_{01}
GGG										
$q\bar{q} \to qg\bar{q}$	2	-2	-2	1	1	0	0	0	0	0
$qg \to qgg$	2	-2	-2	1	1	0	-1	$\frac{5}{2}$	-1	$\frac{3}{2}$
$gg \to ggg$	2	-2	-2	1	1	-1	-1	$\frac{8}{3}$	-1	-1
$qg \to q\bar{q}'q'$	0	0	$\frac{1}{2}$	0	-1	0	1	$-\frac{1}{2}$	1	0
$gg \to g\bar{q}q$	0	0	$\frac{1}{2}$	0	-1	0	1	-1	1	$\frac{1}{2}$
ARIADNE										
$q\bar{q} \to qg\bar{q}$	2	-2	-2	1	1	0	0	0	0	0
$qg \to qgg$	2	-2	-3	1	3	0	-1	0	0	0
$gg \to ggg$	2	-3	-3	3	3	-1	-1	0	0	0
$qg \to qq'q'$	0	0	$\frac{1}{2}$	0	-1	0	1	-1	1	$\frac{1}{2}$
$gg \to g\bar{q}q$	0	0	$\frac{1}{2}$	0	-1	0	1	-1	1	$\frac{1}{2}$
ARIADNE2 (reparametrization of ARIADNE functions à la GGG, for comparison)										
$q\bar{q} \to qg\bar{q}$	2	-2	-2	1	1	0	0	0	0	0
$qg \to qgg$	2	-2	-2	1	1	0	-1	-1	0	0
$gg \to ggg$	2	-2	-2	1	1	-1	-1	$-\frac{4}{3}$	-1	-1

Table 1: Laurent coefficients for massless LL QCD antennae ($\hat{a}\hat{b} \to arb$). The coefficients with at least one negative index are universal (apart from a reparametrization ambiguity for gluons). For "GGG" (the defaults in VINCIA), the finite terms correspond to the specific matrix elements considered in [4]. In particular, the $q\bar{q}$ antenna absorbs the tree-level $Z \to qg\bar{q}$ matrix element [5] and the gg antennae absorb the tree-level $h^0 \to gg \to ggg$ and $h^0 \to gg \to g\bar{q}q$ matrix elements [6]. The

MC4BSM



Monte Carlo Tools for Beyond the Standard Model Physics

ORGANIZERS:
mc4bsm.AT.phys.ufl.edu

RESOURCES:

- Video Lectures on Monte Carlo for the LHC
- BSM tool repository
- Summary of MC4BSM-1

3rd workshop: MARCH 10-11, 2008 (CERN)

Note: both days will be full days. Participants who don't want to miss anything should plan on arriving Mar 9 and leaving Mar 12.

Organizing committee: Georges Azuelos, Christophe Grojean, Jay Hubisz, Borut Kersevan, Joe Lykken, Fabio Maltoni, Konstantin Matchev, Filip Moortgat, Steven Mrenna, Maxim Perelstein, Peter Skands : mc4bsm.AT.phys.ufl.edu

Main Focus: Alternative (non-MSSM) TeV scale physics models

http://theory.fnal.gov/mc4bsm/