Vincia: A new parton shower and matching algorithm

In collaboration with David Kosower, Peter Skands
(**arXiv:0707.3652** [hep-ph])

- The new Vincia shower
- The pure Vincia shower
- The matched Vinca shower
- The full Vincia shower

The new Vincia shower

Why a new parton shower ?

- The CDF/D0 top search showed that neither the parton level ME generators or shower MC's are sufficient for modern phenomenology.
- The combined (or matched) description is needed to give an unified description of the perturbative side of the MC generators.
- Traditional MC generators were developed well before the need of matched predictions and were viewed as complementary to fixed order predictions
- As a consequence the traditional MC generator included QCD inspired "enhancements" to emulate the missing hard physics.
- This complicates the matching of the LO/NLO parton level generators.
- A new parton shower, build with matching in mind, is needed.

The new Vincia shower

The Vincia shower is constructed with matching in mind:

- A “simplified” shower (no emulation of hard physics) such that matching is relatively straightforward.
- For matching a good understanding of the shower algorithm is needed: a strict implementation of a Markovian formulated shower is needed. This makes all properties derivable.
- New tree-level and one-loop amplitude calculations can be inserted as is (without any adjustments).
- All “choices” in constructing the shower are made explicit. This allows an end-user to probe the associated uncertainties.
- A more universal treatment of the hadronization cut-off.

The new Vincia shower

```
// vincia01:
// This is a simple test program to run Z decays at LEP I
// Adapted from: main09.cc (Copyright T. Sjostrand 2007)

// PYTHIA and VINCIA include files, do not uncomment.
#include "Vincia.h"

// Use Pythia8 and Vincia namespaces, for convenience.
using namespace Pythia8;

// Main Program
int main() {

  // Generator with plug-in
  Pythia pythia;
  VinciaPlugin vincia(&pythia,"vincia01.cmnd");

  // Everything from here on is normal Pythia8

  // Shorthands
  Event& event = pythia.event;
  Settings& settings = pythia.settings;

  // Extract settings to be used in the main program.
  double eCM       = settings.parm("Main:eCM");
  int    nEvent    = settings.mode("Main:numberOfEvents");
  int    nShow     = settings.mode("Main:timesToShow");
  bool   vinciaOn  = settings.flag("Vincia");
  bool   primAna   = settings.flag("AntennaShower:analyticPrimitive");

  // Initialize
  pythia.init( 11, -11, eCM);

  // List changed settings
  pythia.settings.listChanged();

  // Check that Z0 decay channels set correctly.
  pythia.particleData.listChanged();
```

- Vincia is constructed as a PYTHIA 8 plug-in
- It uses the general framework of PYTHIA 8.
- It uses all non-perturbative modeling of PYTHIA
- The whole input/output is identical.
- If you have PYTHIA 8 running, the VINCIA plug-in will run inside it without altering the PYTHIA 8 source code.
- It will give you access to a large array of matched LO/NLO parton level generators.
- It gives access to leading-log shower uncertainty analysis.

The pure Vincia shower

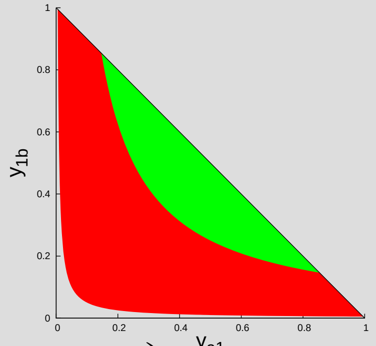
- Soft/collinear radiation in QCD is a dipole radiation: i.e. the emitted parton lives in the dipole field of 2 color connected hard partons (resulting in branchings).
- This description allows for easy matching to fixed order.
- This is close to ARIADNE (as far as the gluonic radiation goes).
- In contrast e.g. HERWIG has collinear emissions ($1\rightarrow2$ branchings) with angular ordering to fix-up the dipole character of the radiation: complicated matching.
- Using a $2\rightarrow3$ brancher allows for on-shell kinematics throughout the shower development (no “virtuality” concept which has no correspondence within a matching procedure).

The pure Vincia shower

The Vincia shower is a numerical implementation of a Markov process.
First we define the Sudakov, i.e the likelyhood of not resolving a new cluster when lowering the resolution scale.

$$\Delta_{\text{event}}\left(\{p_i\}_{i=1}^{n};t_2,t_1;Q_H^2\right)=\prod_{\text{i}\in\text{dipoles}}\Delta^{(i)}_{p_a p_b\to\hat{p}_a\hat{p}_1\hat{p}_b}\left(t_2,t_1;Q_H^2\right)$$

We have an ordering scale or resolution scale which evolves the event to a finer and finer resolution until the event hadronizes…



$$\Delta^{(i)}_{ab}\left(t_2,t_1;q^2_{\text{cut}}\right)=\exp\left(-\int ds_a\int ds_b\int\frac{d\phi}{2\pi}\frac{\alpha_S N_C}{2\pi}\text{Ant}(s_a,s_b,\phi)\times\text{Veto}(s_a,s_b,\phi)\right)$$

$$\text{Veto}(s_a,s_b,\phi)=\Theta\left(Q_R^2(s_a,s_b)-t_2\right)\Theta\left(t_1-Q_R^2(s_a,s_b)\right)\Theta\left(s_{ab}-s_a-s_b\right)\Theta\left(Q_H^2(s_a,s_b)-q^2_{\text{cut}}\right)$$

The pure Vincia shower

- Branching probability is given by the antenna-dipole radiation function:

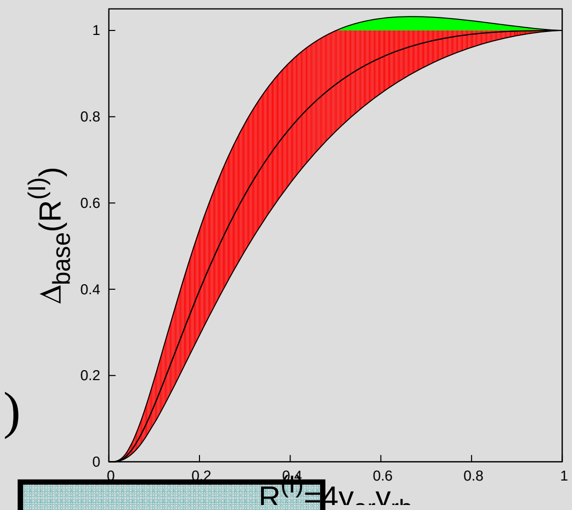
$$\mathrm{Ant}(y_a, y_b) = (1 - y_a - y_b) \times \left(\frac{1}{y_a y_b} + \frac{y_a}{2y_b} + \frac{y_b}{2y_a} \right) + F(y_a, y_b)$$

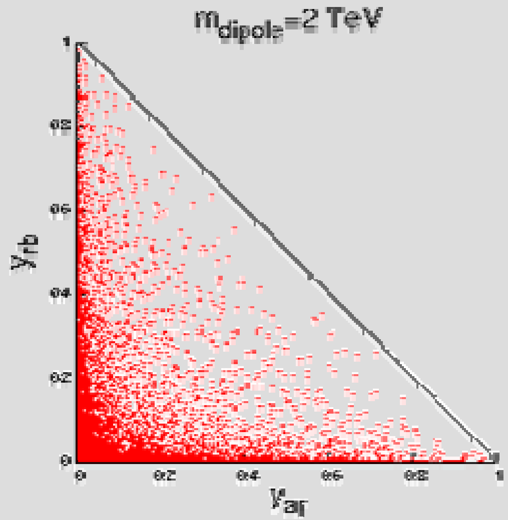
Fixed by QCD

- The radiation function is fixed on the soft/collinear boundary, elsewhere it is arbitrary:

$$F(y_a, y_b) = \sum_{m,n=0} C_{mn} \times y_a^m y_b^n$$

- The antenna function is a Laurent series where the singular parts are fixed by QCD.





The pure Vincia shower

The Markov process is now given by a shower function:

$$S_n\left(\{p_i\}_{i=1}^{n}; Q_R^2; q_{cut}^2 \mid \mathrm{O}\right) = \delta\left(\mathrm{O} - \mathrm{O}\left(\{p_i\}_{i=1}^{n}\right)\right) \Delta_{\text{event}}\left(\{p_i\}_{i=1}^{n}; 0, Q_R^2; q_{cut}^2\right)$$

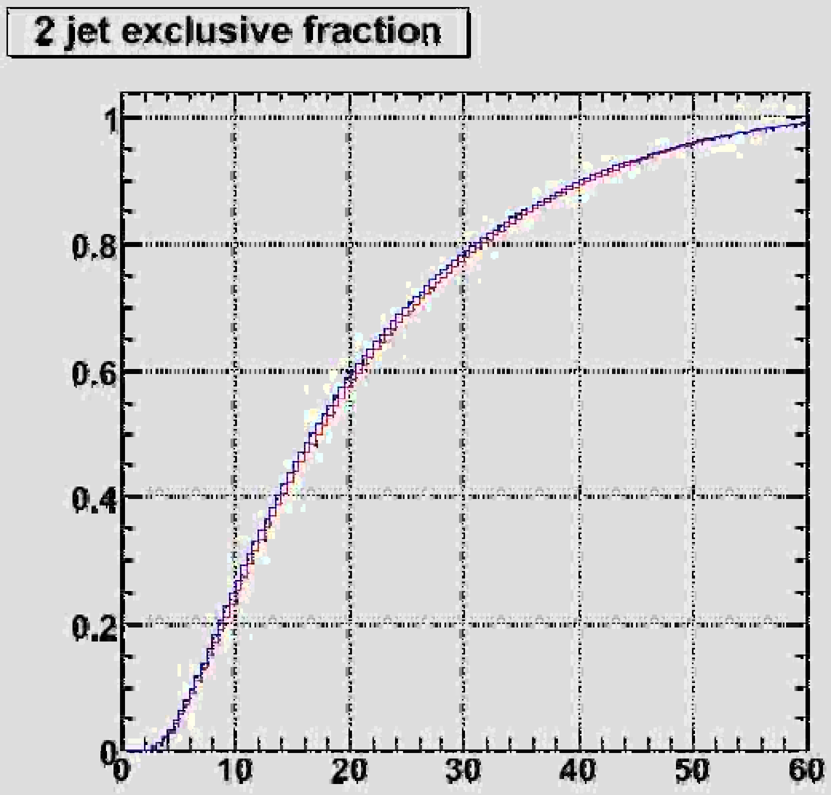
$$+ \int_0^{Q_R^2} dt \left.\frac{\partial \Delta_{\text{event}}\left(\{p_i\}_{i=1}^{n}; t_b, Q_R^2; q_{cut}^2\right)}{\partial t_b}\right|_{t_b = t} \otimes S_{n+1}\left(\{\hat{p}_i\}_{i=1}^{n+1}; t; q_{cut}^2 \mid \mathrm{O}\right)$$

- Changing the finite terms of the antenna functions makes the shower softer/harder. In the pure shower nothing compensates this variation. One would have to tune to data.

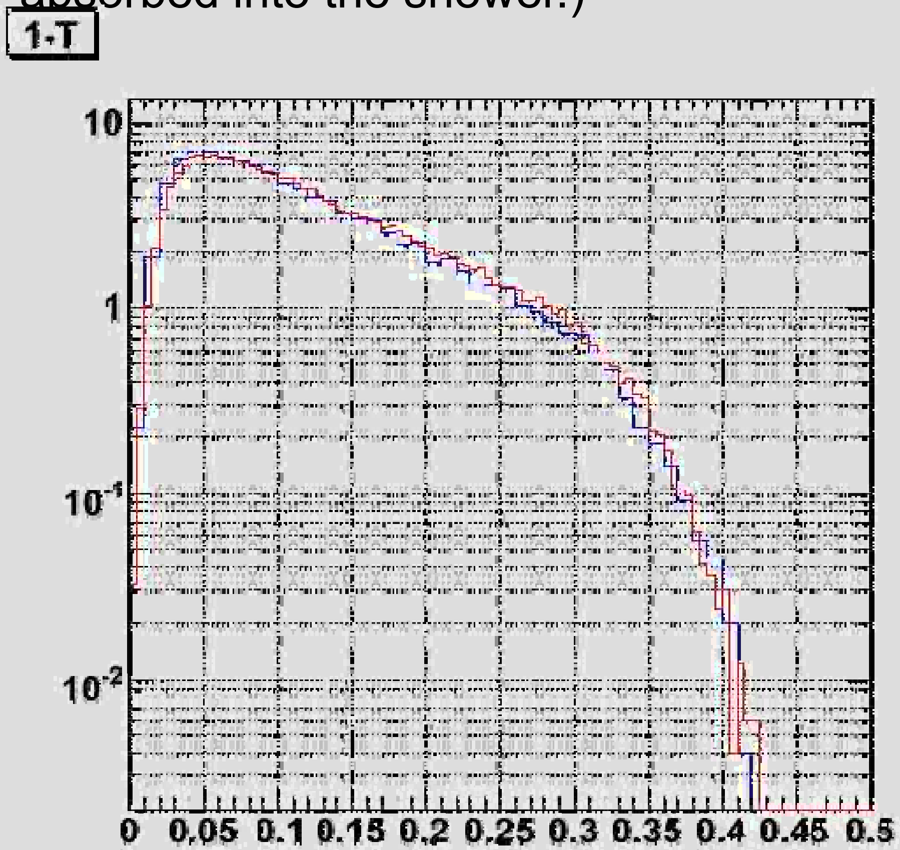
- However, theory itself removes this uncertainty through matching !! This makes the shower far more predictive.

- Because the shower is the numerical MC implementation of this Markov chain we can derive LO/NLO matching conditions and other properties of the shower by expanding the chain in number of branches and/or virtuality.

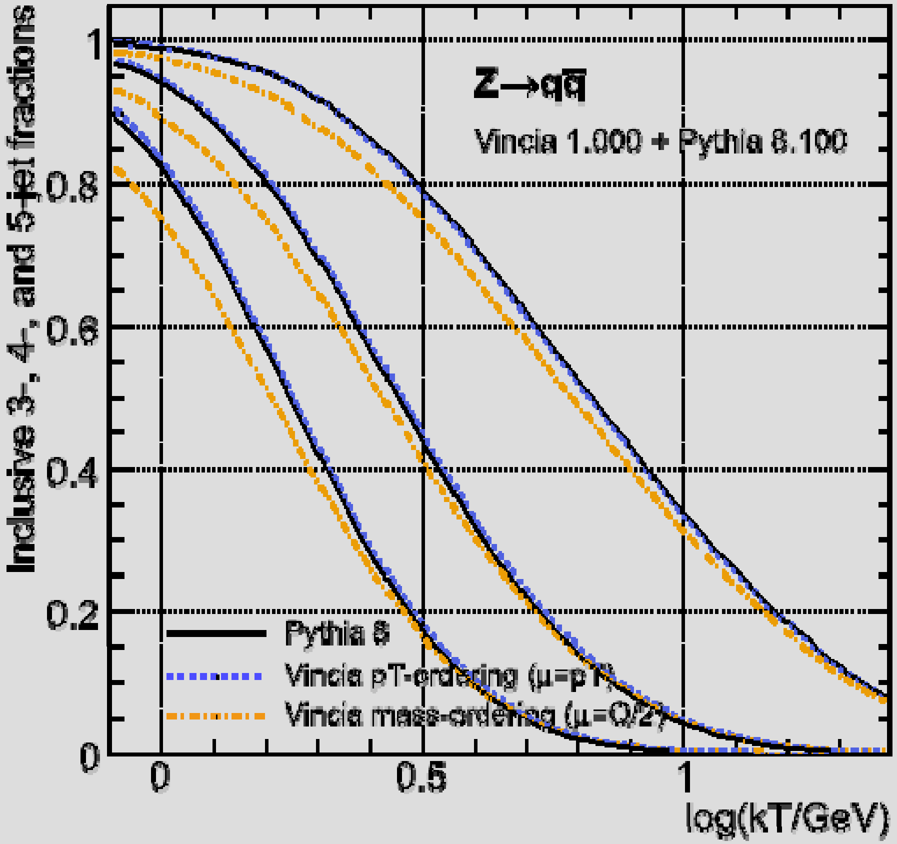
The pure Vincia shower



- Comparison between PYTHIA 8.1 (default settings) and Vincia (default settings) for gluonic cascade showers.
- (The default Vincia settings are such that the H → 3 gluon matrix element is absorbed into the shower.)

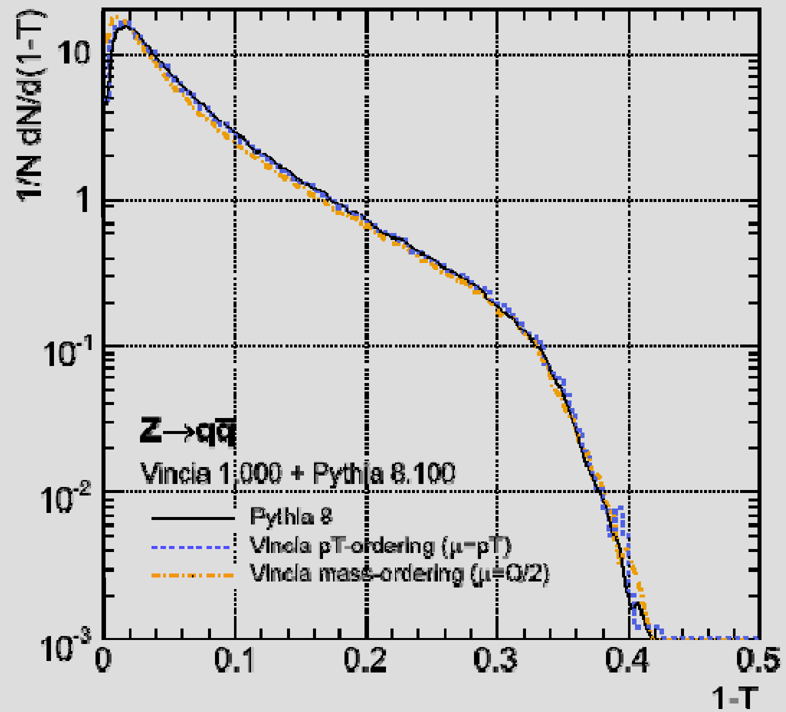


The pure Vincia shower

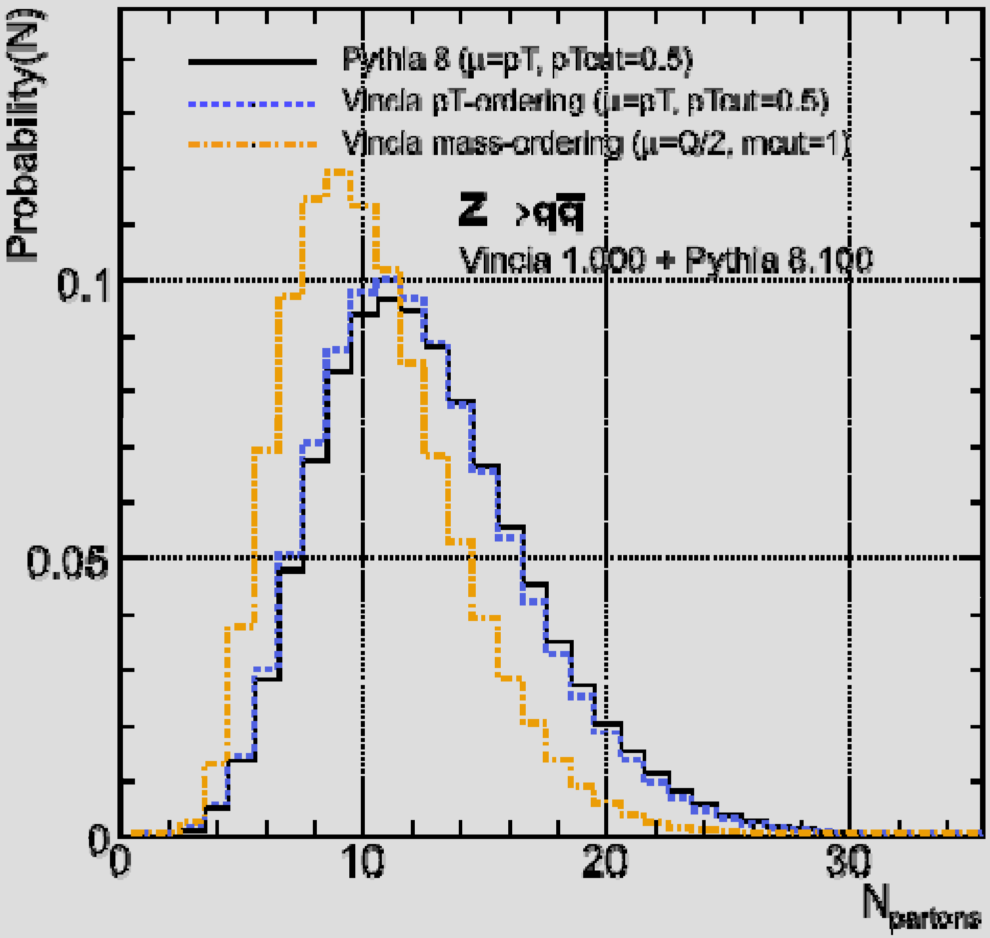


- Comparison between PYTHIA 8.1 (default settings) and Vincia (default settings) for e+e- → (u,d,g)-partons.
- (The default Vincia settings are such that the Z → qgq matrix element is absorbed into the shower….)

1-T

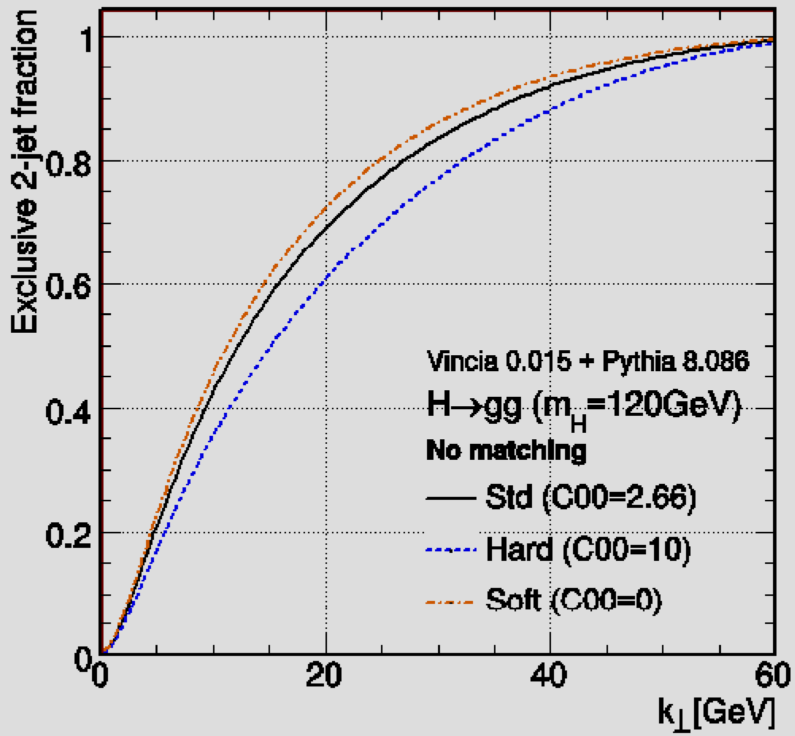


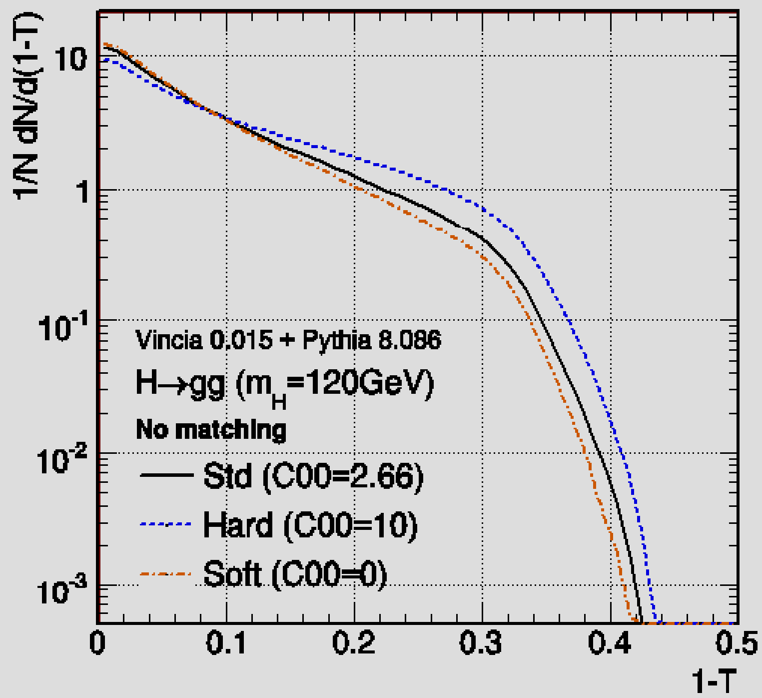
The pure Vincia shower



- Comparing the final parton multiplicities
- This is not an observable or even an infrared safe quantity
- Yet Vincia pure shower can reproduce PYTHIA shower
- This actually tells us we can even use the PYTHIA hadronization model fits without much retuning…

The pure Vincia shower



- As mentioned before the hardness of the shower is not determined.
  This leading to large uncertainties in the predictions.
- 

The matched Vincia shower

Matching is simply given by the condition

$$\frac{d\sigma}{dO} = \sum_{n=2}\sum_{l=0}\int d\,PS_n\; S\big(p_1,\ldots,p_n;Q_n^2;q_{cut}^2\,|\,O\big)\,|\,\tilde{m}_n^{(l)}\,|^2$$

$$= \sum_{n=2}\sum_{l=0}\int d\,PS_n\; \delta\big(O(p_1,\ldots,p_n)-O\big)\,|\,m_n^{(l)}\,|^2$$

MC@NLO on steroids

- By expanding out S in number of branchings and virtuality we get the matching conditions: $|\,\tilde{m}_n^{(l)}\,|^2 = |\,m_n^{(l)}\,|^2 + C_n^{(l)}$
- The subtracted matrix elements are now finite in the soft/collinear limit of a parton.
- The matching term depends on the hardness of the antenna function (and consequently the hardness of the shower).
- This causes the a cancellation of the dependence of the observable on the arbitrary choices made in the antennae functions.

The matched Vincia shower

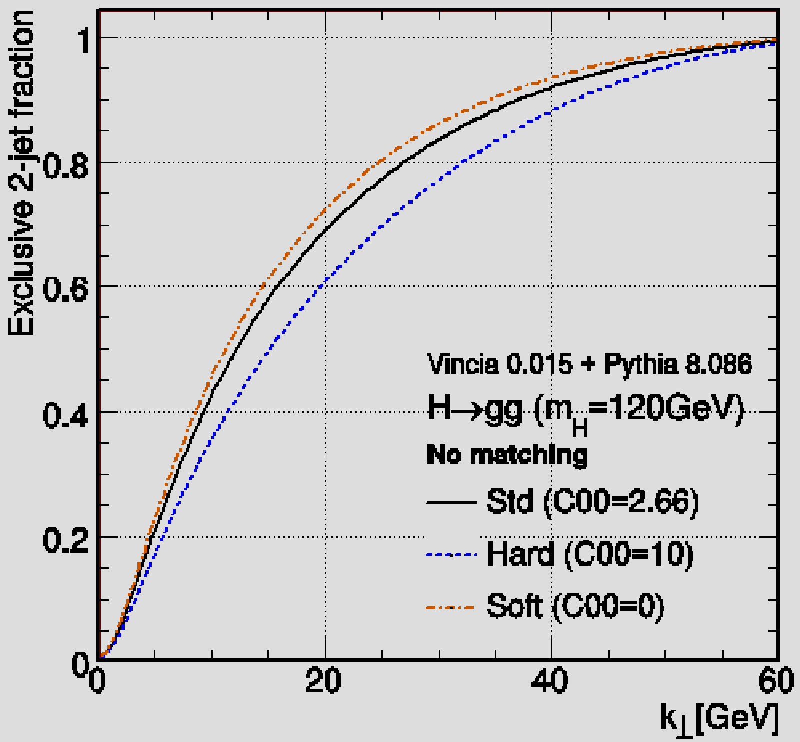
There are more unexpected results:

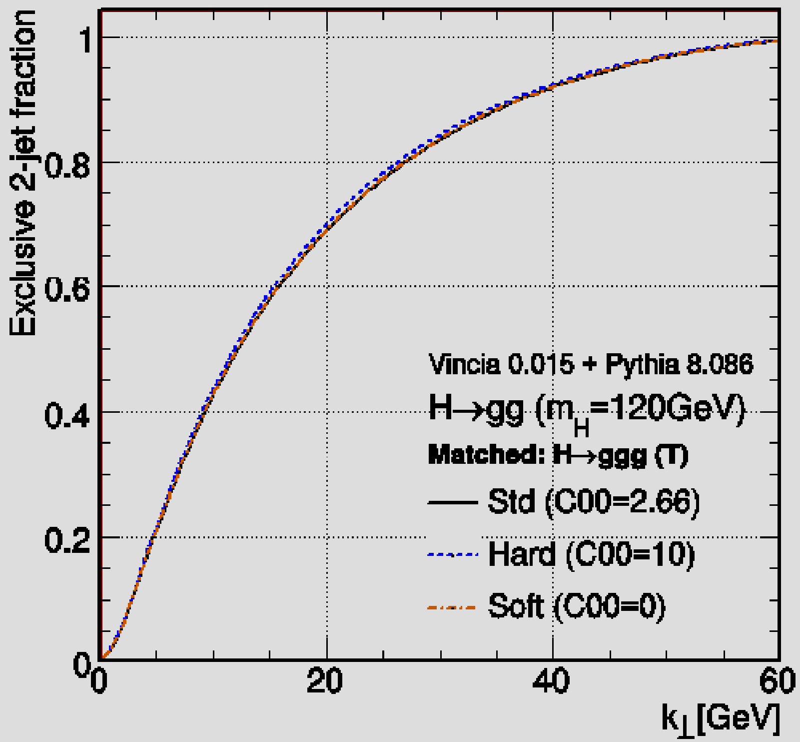
- The shower starting scale is determined by the evolution variable choice (e.g at which scale to start the shower for 4 partons is **not** a choice).
- Color factors (C_A or C_F) become more “dynamically” generated.

One still require a double unresolved regulator (sub-leading logs).

As this is sub-leading the dependence of the observable on this regulator is small.

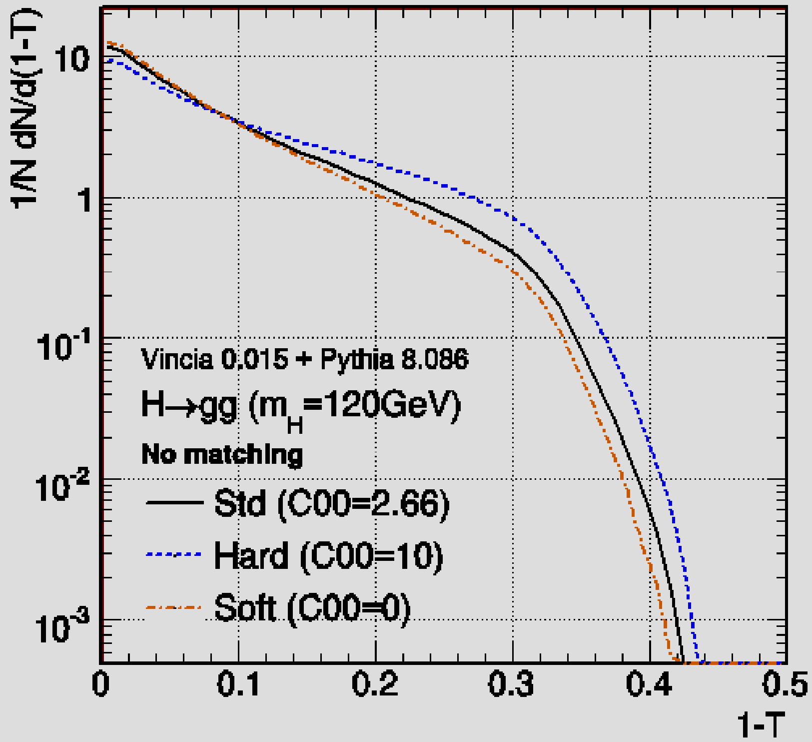
The matched Vincia shower

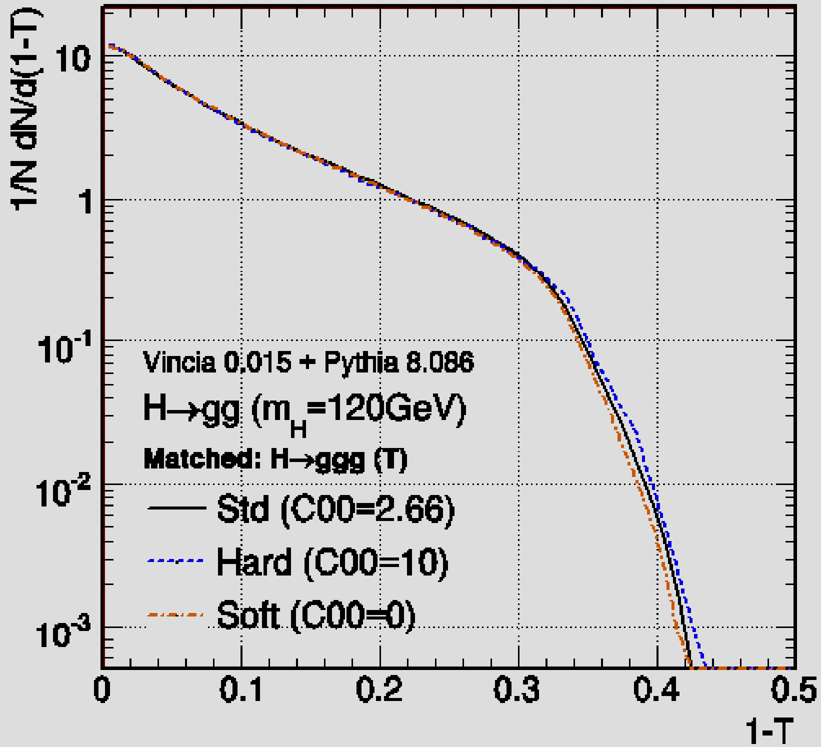




Matching at work; by just matching the shower with the tree-level 3-gluon matrix we remove most of the uncertainty.
If needed more hard matrix elements can be included to bring the uncertainty below an (expected) experimental uncertainty.

The matched Vincia shower





Same for the thrust distribution.

Note that for larger values we can further reduce the uncertainty by matching to higher gluon multiplicity matrix elements.

The full Vincia shower

We are working towards the first publicly available Vincia plug-in:

- e+e- collider shower.
- The pure shower is finished and agrees well with PYTHIA.
- allows for matching to e+e- $\rightarrow$ 2,3,4,5 partons at LO (in progress).
- allows for matching to e+e- $\rightarrow$ 2,3,4 partons at NLO (in progress).
- MADGRAPH generator interface (in progress).
- On-the-fly refitting of hadronization model (including uncertainties).
- Can estimate uncertainties due to all input parameter choices.
- Highly customizable by end user (adding new types of branchings, evolution scales,…)

The full Vincia shower

The Vincia parton shower depends on a limited set of input parameters:

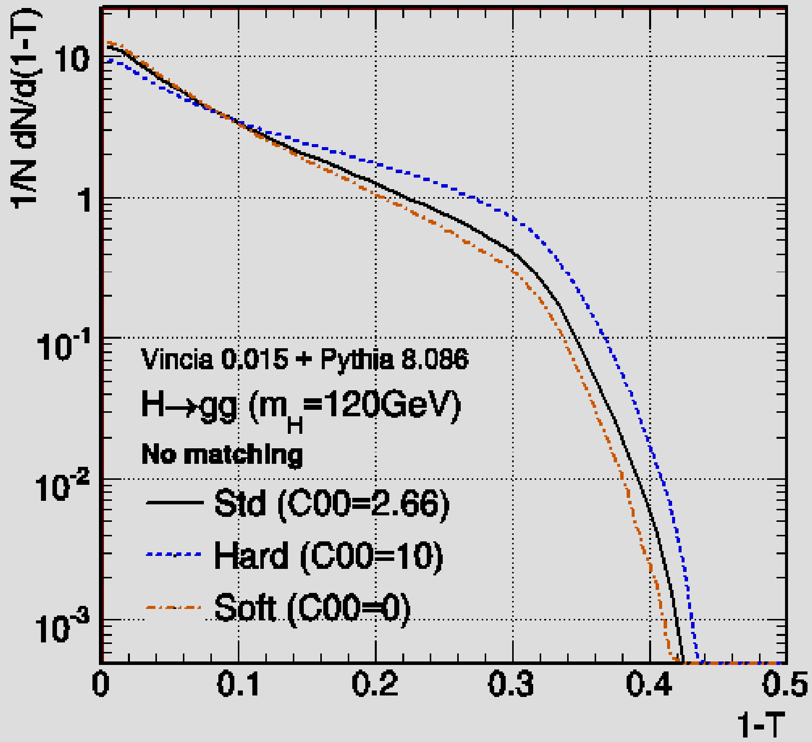
- Antenna hard radiation choice (i.e. shower hardness): this dependence can be avoided by matching
- Strong coupling constant scale choice: partly canceled by including NLO matrix elements, partly dependent on leading log approximation
- Evolution scale choice dependence: dependence due to leading log approximation
- Double clustering regulator: dependence due to leading log approximation and absence of NNLO matrix elements
- Hadronization scale: outside the realm of perturbative description.

The NNLO e+e- → 3 jets has been calculated within the antenna framework. This means we can construct the next-to-leading log shower. This would address all uncertainties except hadronization modeling.

Conclusions

- A public Vincia plug-in will be available soon as an extention to PYTHIA 8
- Adding the Vincia plugin to PYTHIA will give you access to a parton shower which
    - Matched LO/NLO matrix elements
    - Allow to vary all input parameters for estimating uncertainties in the leading-log shower
- Puts all remaining, unexplained deviations on non-perturbative understanding…

The full Vincia shower



- As an example we show the evolution scale dependence.
- As such a dependence is beyond the leading log approximation the effects are rather small.
- However, this is not guaranteed for all observables.
- Vincia allows you to probe this uncertainty to see if this an issue in the prediction.