PYTHIA 8
Physics and Technical Aspects

P. Z. Skands (CERN-TH)

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PYTHIA 8

Ambition

- **Cleaner** code
- More user-friendly
- Easy **interfacing**
- Physics Improvements

Current Status

- Ready and tuned for Min-Bias (+ diffraction improved over Pythia 6)
- Improved shower model, but bug/problem with underlying event?

Team Members

- Stefan Ask
- Richard Corke
- Stephen Mrenna
- Torbjorn Sjostrand
- Peter Skands

Contributors

- Bertrand Bellenot
- Lisa Carloni
- Tomas Kasemets
- Mikhail Kirsanov
- Ben Lloyd
- Marc Montull
- Sparsh Navin
- MSTW, CTEQ, H1: PDFs
- DELPHI, LHCb: D/B BRs
- + several bug reports & fixes

Physics (1/3)

Perturbative Resonance Decays

- Angular correlations often included (on a process-by-process basis - no generic formalism)
- User implementations *(semi-internal resonance)*

Physics (1/3)

Hard Physics

- SM
  - almost all 2→1
  - almost all 2→ 2
  - A few 2→3
- BSM: a bit of everything *(see documentation)*

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External Input

- Les Houches Accord and LHEF *(e.g., from MadGraph, CompHEP, AlpGen,…)*
- User implementations *(semi-internal process)*
  - Inheriting from PYTHIA's 2→2 base class, then modify to suit you

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Physics (2/3)

[T. Kasemets, arXiv:1002.4376]

Physics (2/3)

Parton Distributions

- Internal *(faster than LHAPDF)*
  - The standard CTEQ and MSTW LO sets, plus a few NLO ones
  - New generation: MSTW LO*, LO**, CTEQ CT09MC **[T. Kasemets, arXiv:1002.4376]**
- Interface to LHAPDF
- Can use separate PDFs for hard scattering and UE *(to 'stay tuned')*

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Showers

- Transverse-momentum ordered ISR & FSR *(new: fully interleaved)*
- Includes QCD and QED
- Dipole-style recoils *(partly new)*
- Improved high-$p_\perp$ behavior **[R. Corke]**

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Matrix-Element Matching

- Automatic first-order matching for most gluon-emission processes in resonance decays, e.g.,:
  - $Z \rightarrow qq \rightarrow qqg$,
  - $t \rightarrow bW \rightarrow bWg$,
  - $H \rightarrow bb \rightarrow bbg$,
  - …
- Automatic first-order matching for internal $2 \rightarrow 1$ color-singlet processes, e.g.:
  - $pp \rightarrow Z/W/Z'/W'$+jet
  - $pp \rightarrow H$+jet
  - More to come …
- Interface to AlpGen, MadGraph, … via Les Houches Accords

Physics (3/3)

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Underlying-Event and Min-Bias

- Multiple parton–parton interactions
  - Multi-parton PDFs constructed from (flavor and momentum) sum rules
  - Combined (interleaved) evolution MI + ISR + FSR downwards in $p_\perp$ *(partly new)*
  - Optional rescattering **[R. Corke]**
- Beam remnants colour-connected to interacting systems
  - String junctions → variable amount of baryon transport
- Defaults tuned to Tevatron MB
- Improved model of diffraction
  - Diffractive jet production **[S. Navin]**

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Hadronization

- String fragmentation
  - Lund symmetric fragmentation function for (u,d,s) + Bowler modification for heavy quarks (c,b)
- Hadron and Particle decays
  - Usually isotropic, or:
  - User decays *(DecayHandler)*
  - Link to external packages
    - EVTGEN for B decays
    - TAUOLA for τ decays
- Bose-Einstein effects
  - Two-particle model *(off by default)*

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Output

- Interface to HEPMC included

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New features, not found in 6.4

- Up-to-date decay data and PDFs
- Underlying Event
  - Interleaved MI + ISR + FSR
  - Richer mix of underlying-event processes (γ, J/ψ, DY, . . .)
  - Possibility for two selected hard interactions in same event
  - Alow parton rescattering
  - Possibility to use one PDF set for hard process and another for rest
- Hard scattering in diffractive systems
- New SM and BSM processes

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Hidden Valley scenario with hidden radiation

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- Some matrix elements, in particular Technicolor, partly SUSY

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Diffraction in PYTHIA 6

Diffractive Cross Section Formulæ:

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta^2_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\;,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g^2_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\;.$$

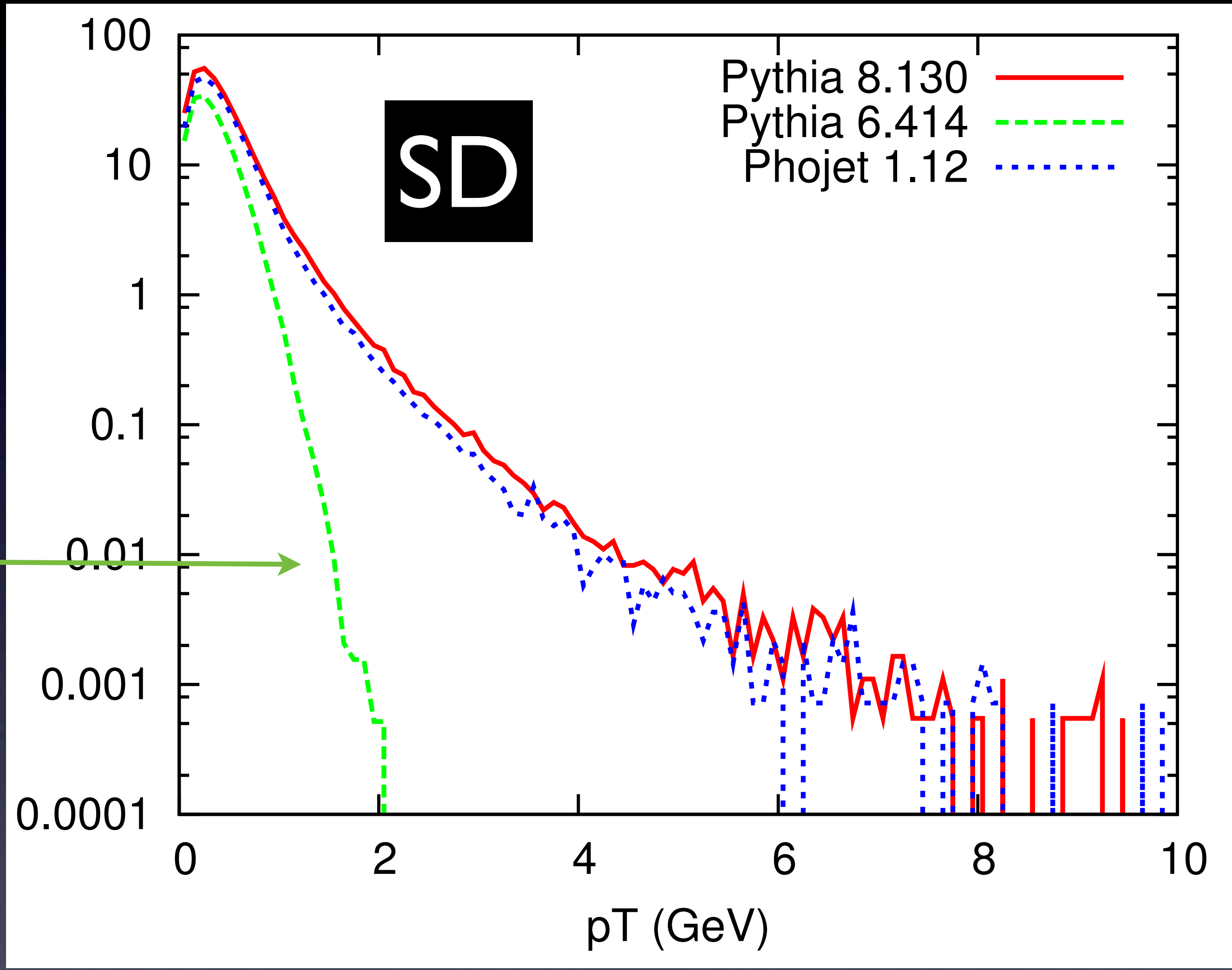
Spectra:

$2\,m_{pi} < M_D < 1$ GeV: 2-body decay

$M_D > 1$ GeV : string fragmentation

Partonic Substructure in Pomeron:

Only in POMPYT addon (P. Bruni, A. Edin, G. Ingelman) ► high-p_T "jetty" diffraction absent



Very soft spectra without POMPYT

Status: Supported, but not actively developed

Diffraction in PYTHIA 8

S. Navin (MCnet) + T. Sjöstrand

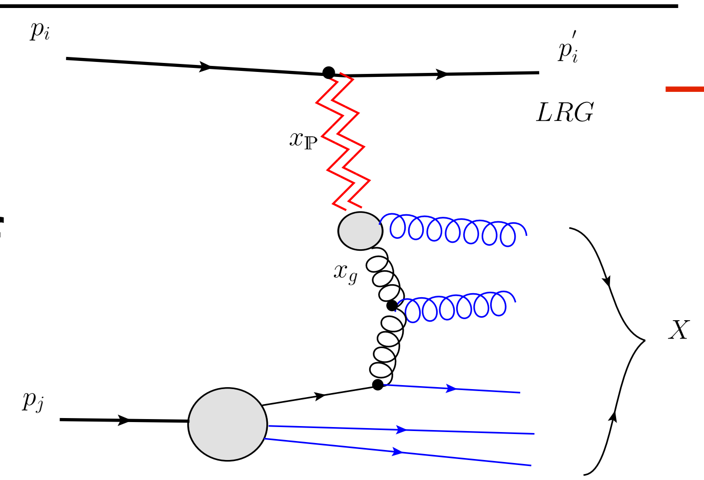
Diffractive Cross Section Formulæ:

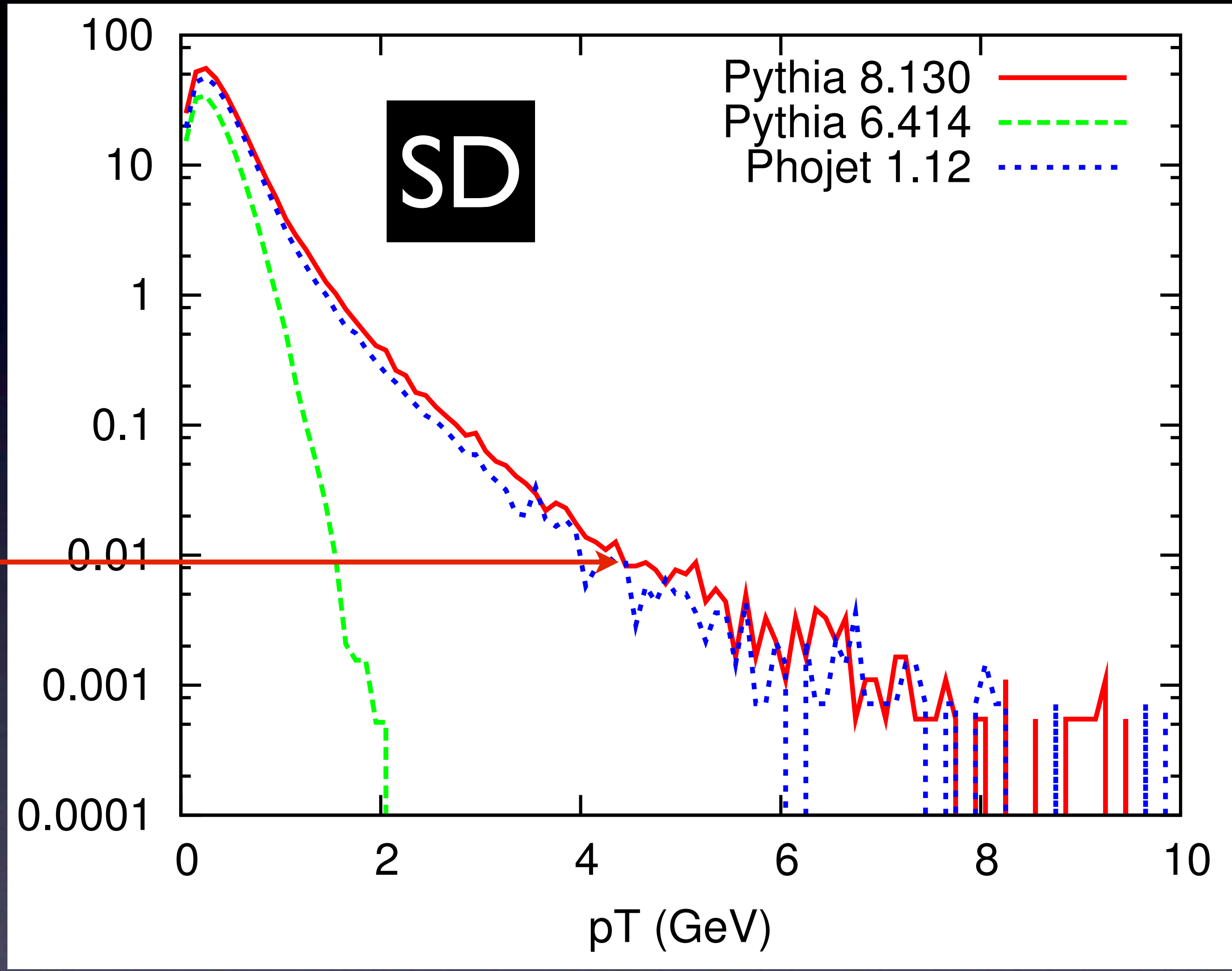
$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi} \beta^2_{A\mathbb{P}} \beta_{B\mathbb{P}} \frac{1}{M^2} \exp(B_{sd(AX)} t)\, F_{sd} ,$$

$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g^2_{3\mathbb{P}}}{16\pi} \beta_{A\mathbb{P}} \beta_{B\mathbb{P}} \frac{1}{M_1^2} \frac{1}{M_2^2} \exp(B_{dd} t)\, F_{dd} .$$

Partonic Substructure in Pomeron:

Follows the approach of Pompyt





- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: new perturbative description used

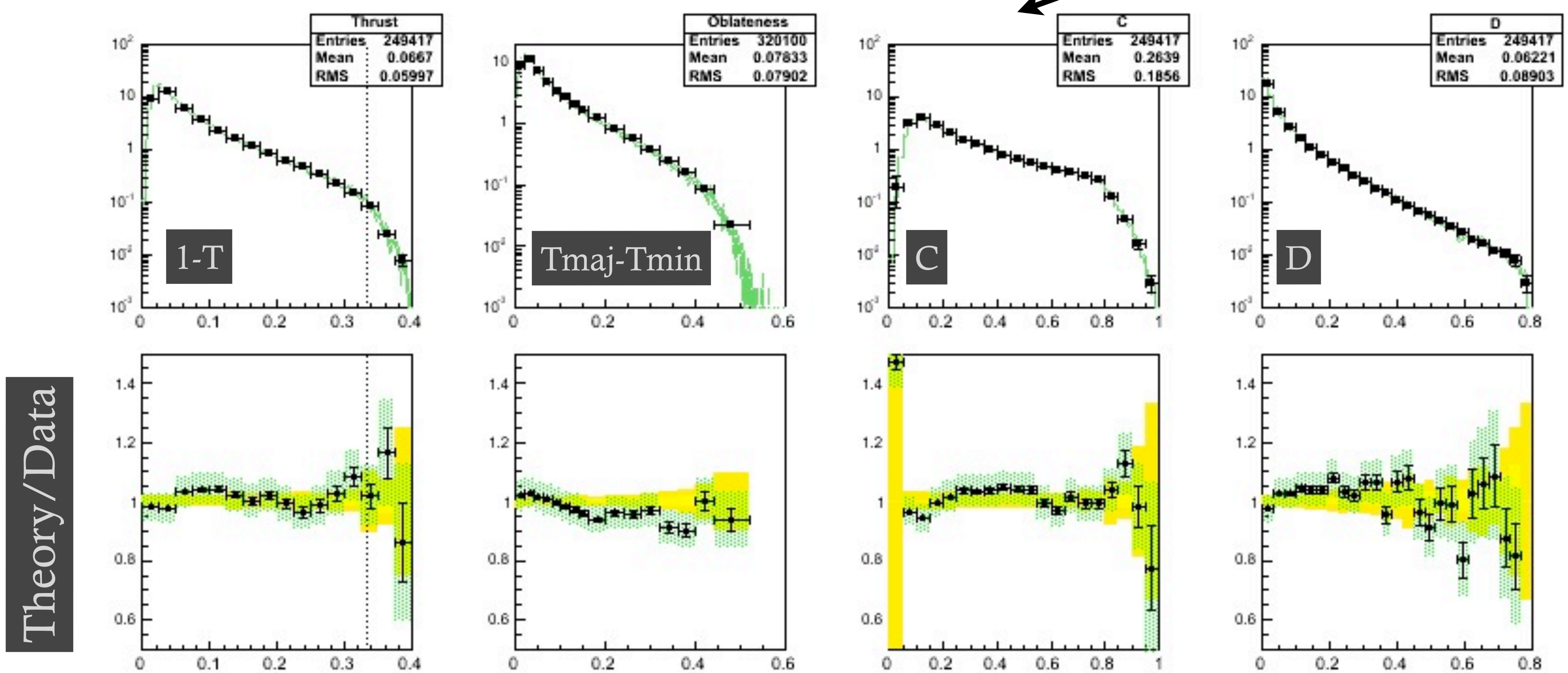
Status: Supported and actively developed

Tuning

Tuning to e^+e^- closely related to $p_\perp$-ordered PYTHIA 6.4

- First tuning by Professor → FSR ok?

(using the Runtime Display from the VINCIA plugin)



Tuning

Tuning to e⁺e⁻ closely related to p⊥-ordered PYTHIA 6.4

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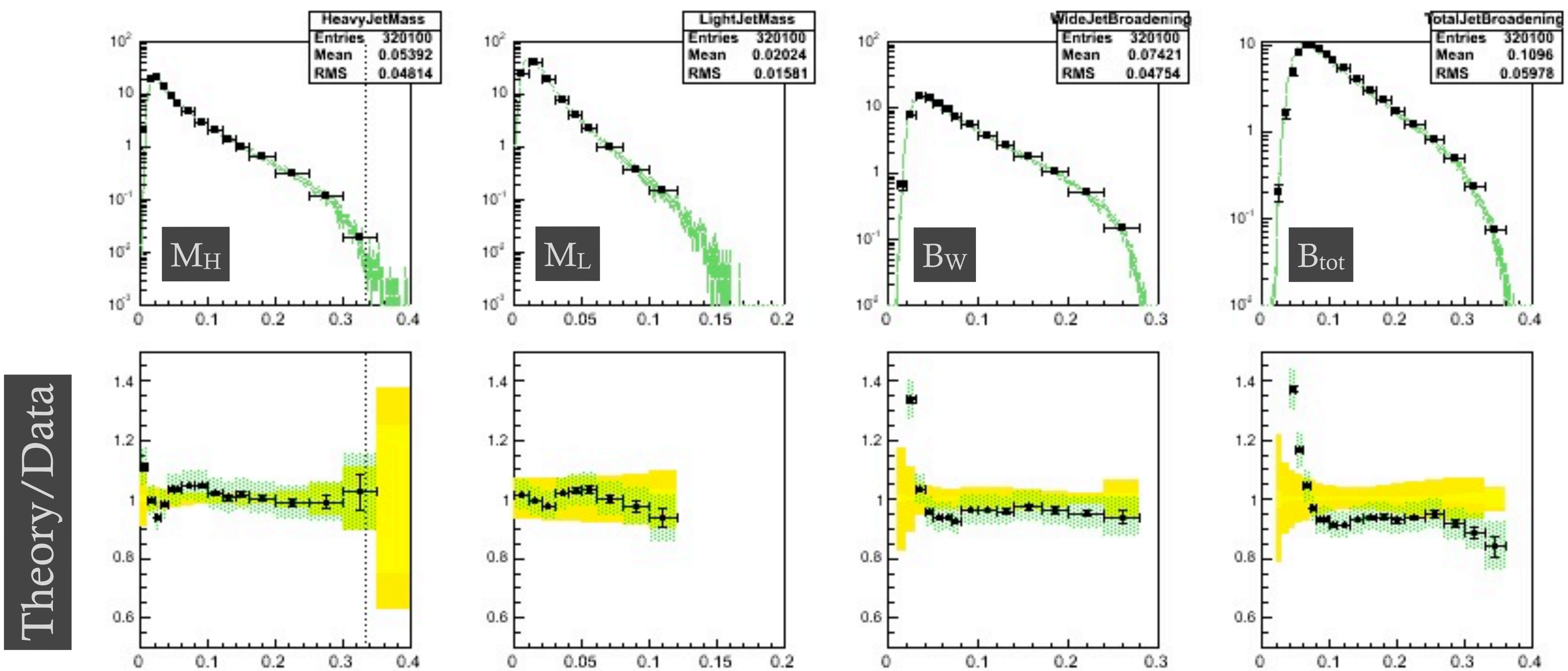

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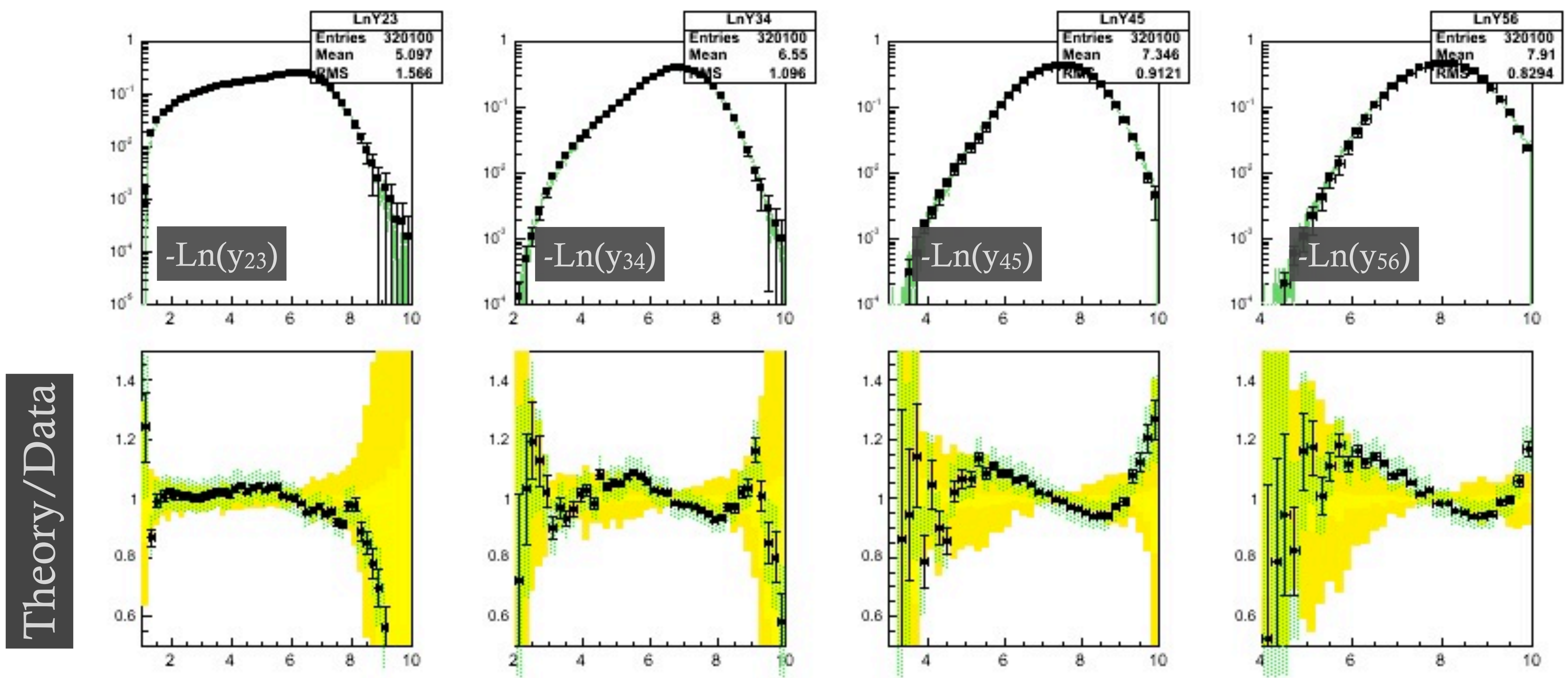
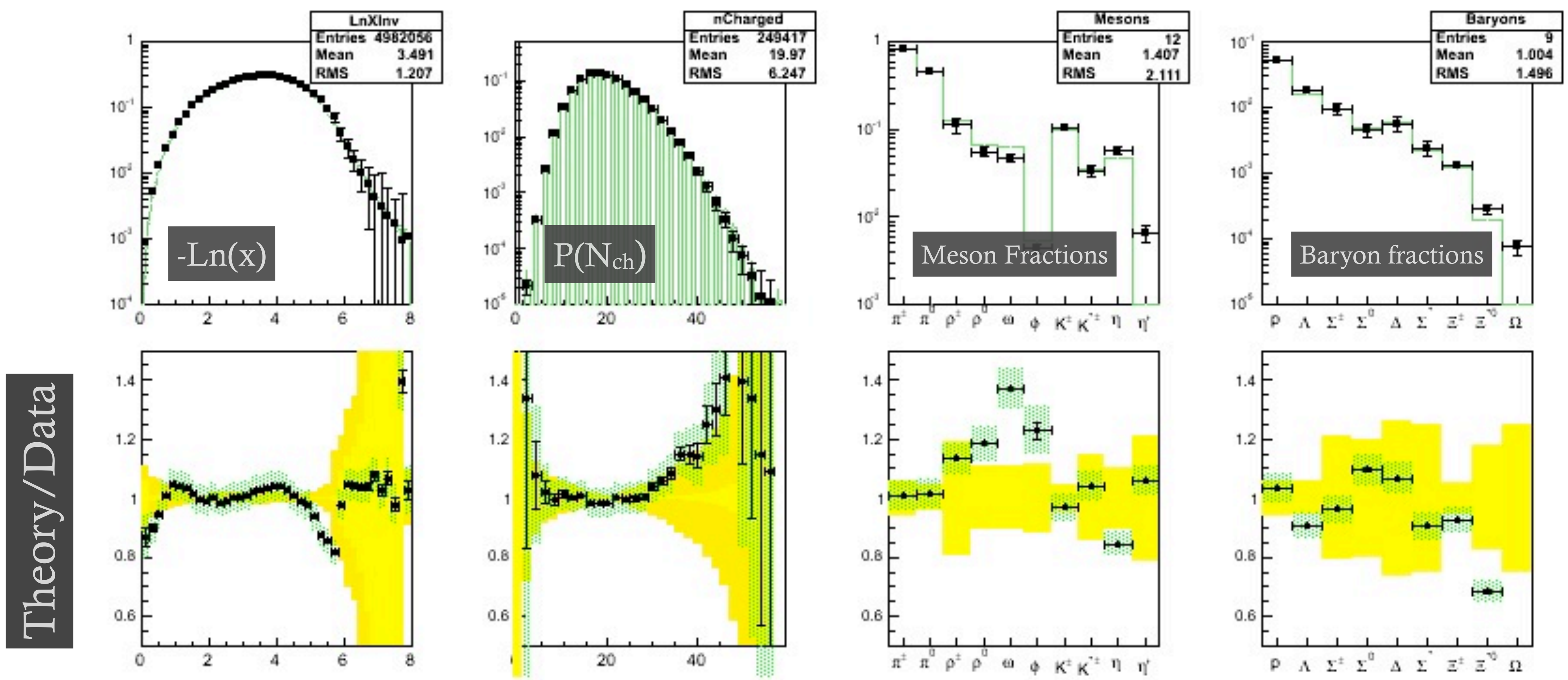


Tuning

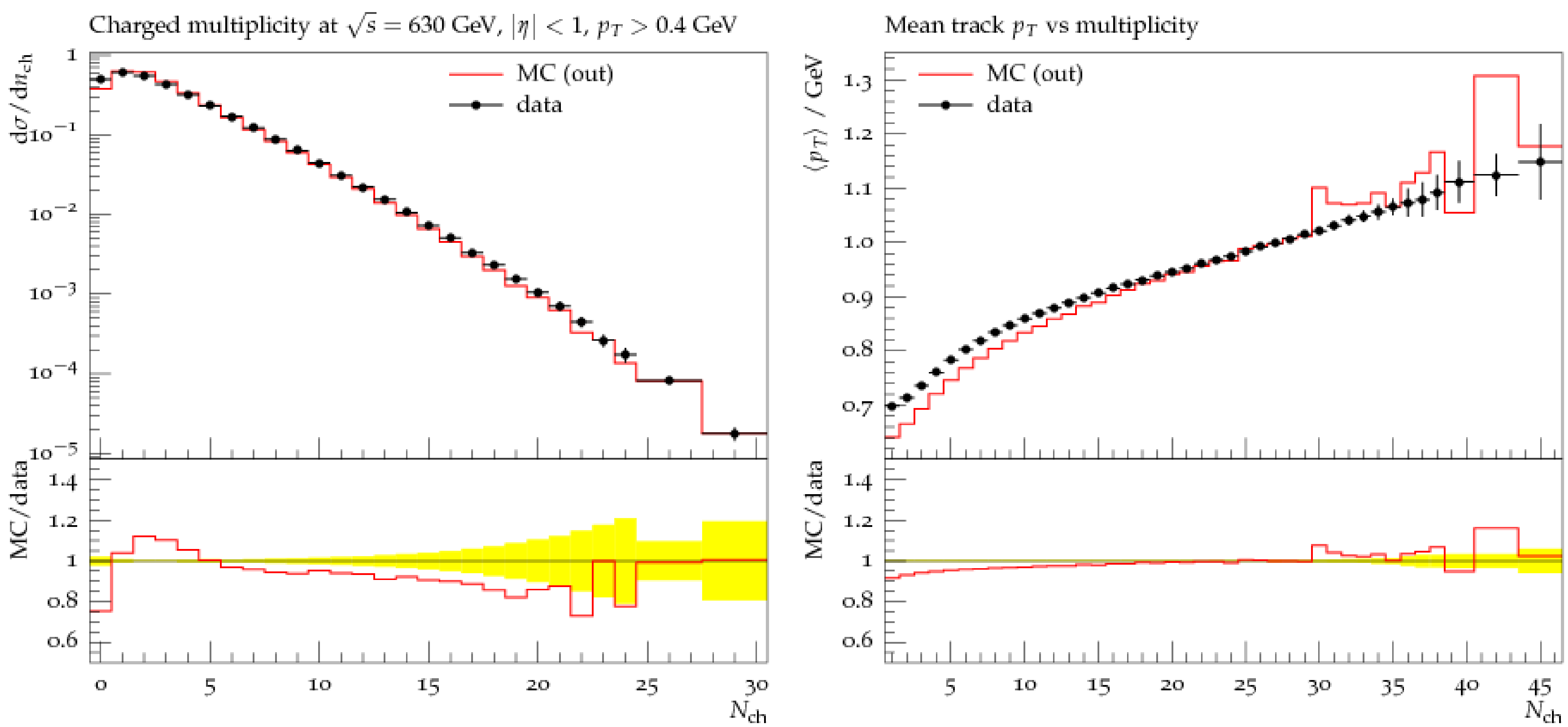
Tuning to e^+e^- closely related to $p_\perp$-ordered PYTHIA 6.4

- First tuning by Professor → Hadronization OK?



Tuning

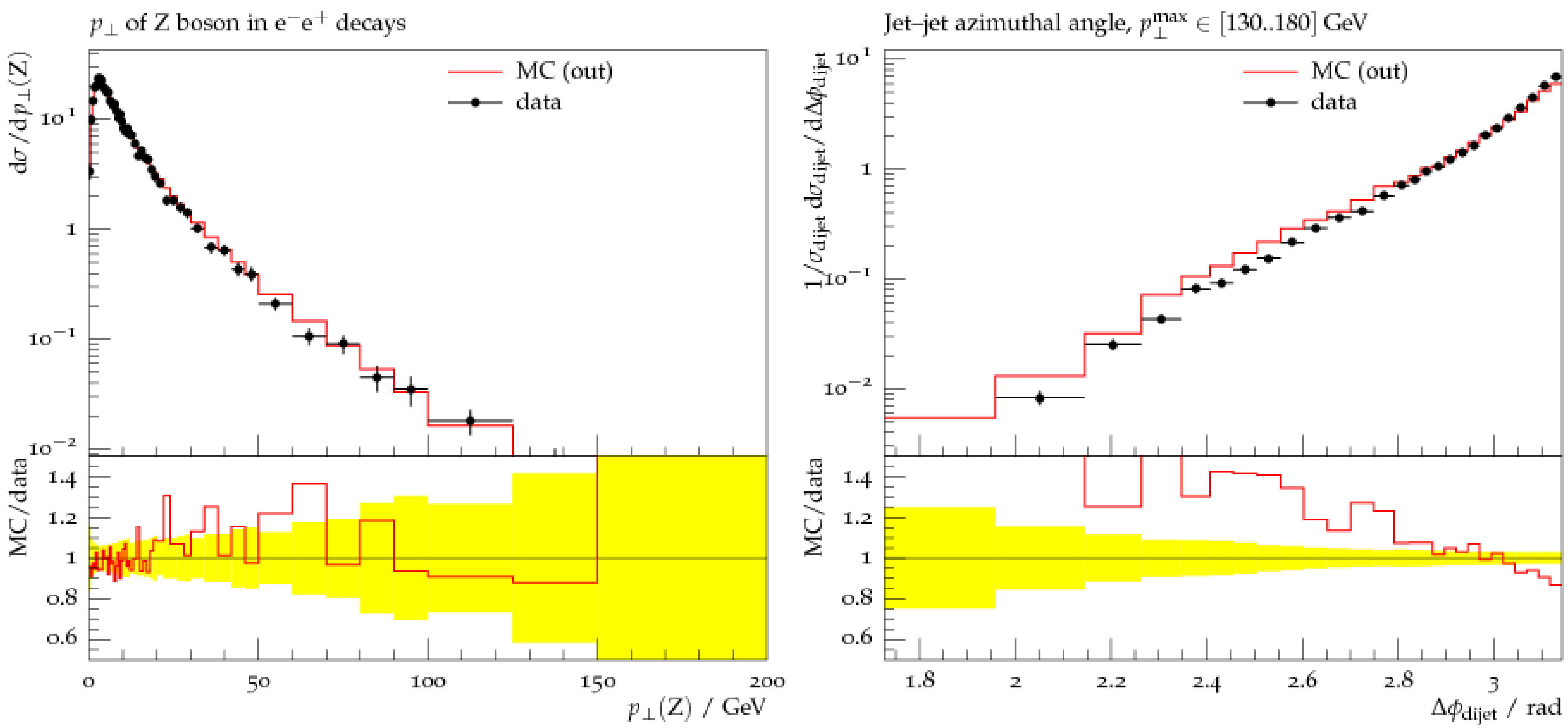
First tuning to MB data (PS)



$\Rightarrow$ MPI & colour reconnection OK (?)

Tuning

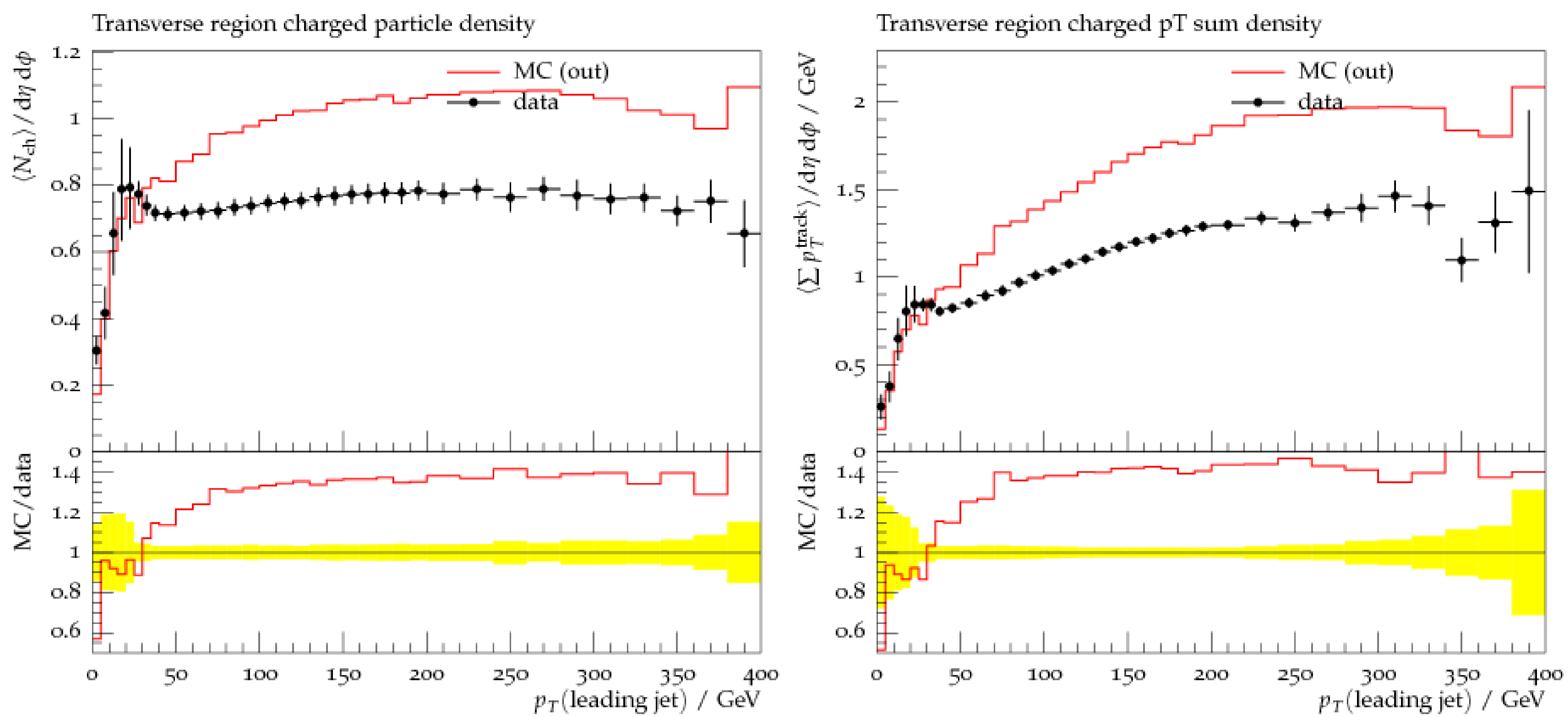
Also works for hard-physics distributions:



⇒ ISR OK (?)

Tuning

But Rivet+Professor (H. Hoeth) shows it fails miserably for UE (Rick Field's transverse flow as function of jet $p_\perp$):



Where did we go wrong?

Studies still ongoing

Technical Aspects

Compilation and Linking

Disk and Memory requirements

Speed and Optimization

Documentation

Compilation and Linking

Default standalone

- You just need a C++ compiler
  - PYTHIA 8 only depends on *stdlib,* no external libraries
  - Can be compiled either as a static (.a) or shared (.so) library
- No static variables
  - Can have multiple instances
- Standard build procedure
  - ./configure
  - make
  - Then move to examples/ subdirectory and open README file

Examples

- ~ 40 example programs included in examples/ subdirectory
- Including how to use each of the interfaces, and more

Optional Dependencies

(examples included)

- FastJet
- LHAPDF
- HepMC
- ROOT

Disk and Memory Requirements

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Disk Space

- Source Code

```
1.8M  src/
544K  include/
 12K  hepmcinterface/
7.0M  xmldoc/
2.1M  htmldoc/
2.4M  phpdoc/
6.0M  examples/
========================
 20M  pythia8135
```

- Libraries *(incl tmp)*

```
3.6M  lib/
4.0M  tmp/archive/
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 28M  pythia8135
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- Executables

```
2.3M  examples/main01.exe
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  - Typical size of standalone executable.
  - Bigger if linked to external packages

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Memory Usage

```
~ 10M standalone
```

- Minimal usage. More if linked to external packages, filling histograms, etc

Speed and Optimization

(on 3GHz processor)

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Compiling PYTHIA 8 (from scratch)

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user    1m23.870s
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Running PYTHIA 8 (with default flags etc)

σ_{tot} = EL+INEL 7 TeV 4 ms/event
Min-Bias 7 TeV 6 ms/event
Drell-Yan ($m \geq 70$GeV) 7 TeV 13 ms/event
Dijets ($p_\perp \geq 100$GeV) 7 TeV 20 ms/event

Multiple Interactions ≥ 50% of total
Hadronization ~ 10% - 20% of total

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Optimization

- Currently no dedicated optimization for multi-core usage

Steering and Settings

1. Defaults

- No hardcoded defaults *(in .cc and .h files)*
- Instead, all default settings read from XML file set
  - Write-protected: **do not change!** (these are the *defaults*)
  - XML → HTML ⇒ User Manual (htmldoc/Welcome.html)
    - Minimal risk of inconsistency
    - Also exists as php with added functionality, but must then be installed on a web server

2. Setting and Changing parameters

- In your code: pythia.readString("parameter = value");
- OR: collect any number of such strings in a cardFile.cmnd and use: pythia.readFile("cardfile.cmnd");

Documentation

Welcome

http://home.thep.lu.se/~torbjorn/php8135/Welcome.php

Welcome

PYTHIA 8 Index

Program Overview

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Main-Program Settings
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PDF Selection
Master Switches
Process Selection
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-- Electroweak
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-- Top
-- Fourth Generation
-- Higgs
-- SUSY
-- New Gauge Bosons
-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Extra Dimensions
A Second Hard Process

PYTHIA 8

Welcome to PYTHIA - The Lund Monte Carlo!

PYTHIA 8 is the successor to PYTHIA 6, rewritten from scratch in C++. With the release of PYTHIA 8.1 it now becomes the official "current" PYTHIA version, although PYTHIA 6.4 will be supported in parallel with it for some time to come. Specifically, the new version has not yet been enough tested and tuned for it to have reached the same level of reliability as the older one. This testing will only happen if people begin to work with the program, however, which is why we encourage a gradual transition to the new version, starting now. There are some new physics features in PYTHIA 8.1, that would make use of it more attractive, but also some topics still missing, where 6.4 would have to be used. Further, many obsolete features will not be carried over, so for some backwards compatibility studies again 6.4 would be the choice.

Documentation

On these webpages you will find the up-to-date manual for PYTHIA 8.1. Use the left-hand index to navigate this documentation of program elements, especially of all possible program settings. All parameters are provided with sensible default values, however, so you need only change those of relevance to your particular study, such as choice of beams, processes and phase space cuts. The pages also contain a fairly extensive survey of all methods available to the user, e.g. to study the produced events. What is lacking on these webpages is an overview, on the one hand, and an in-depth physics description, on the other.

The overview can be found in the attached PDF file
A Brief Introduction to PYTHIA 8.1
T. Sjöstrand, S. Mrenna and P. Skands, Comput. Phys. Comm. 178 (2008) 852 [arXiv:0710.3820].
You are strongly recommended to read this summary when you start out to learn how to use PYTHIA 8.1. Note that some details have changed since the 8.100 version described there.

For the physics description we refer to the complete
PYTHIA 6.4 Physics and Manual
T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026,
which in detail describes the physics (largely) implemented also in PYTHIA 8, and also provides a more extensive bibliography than found here.

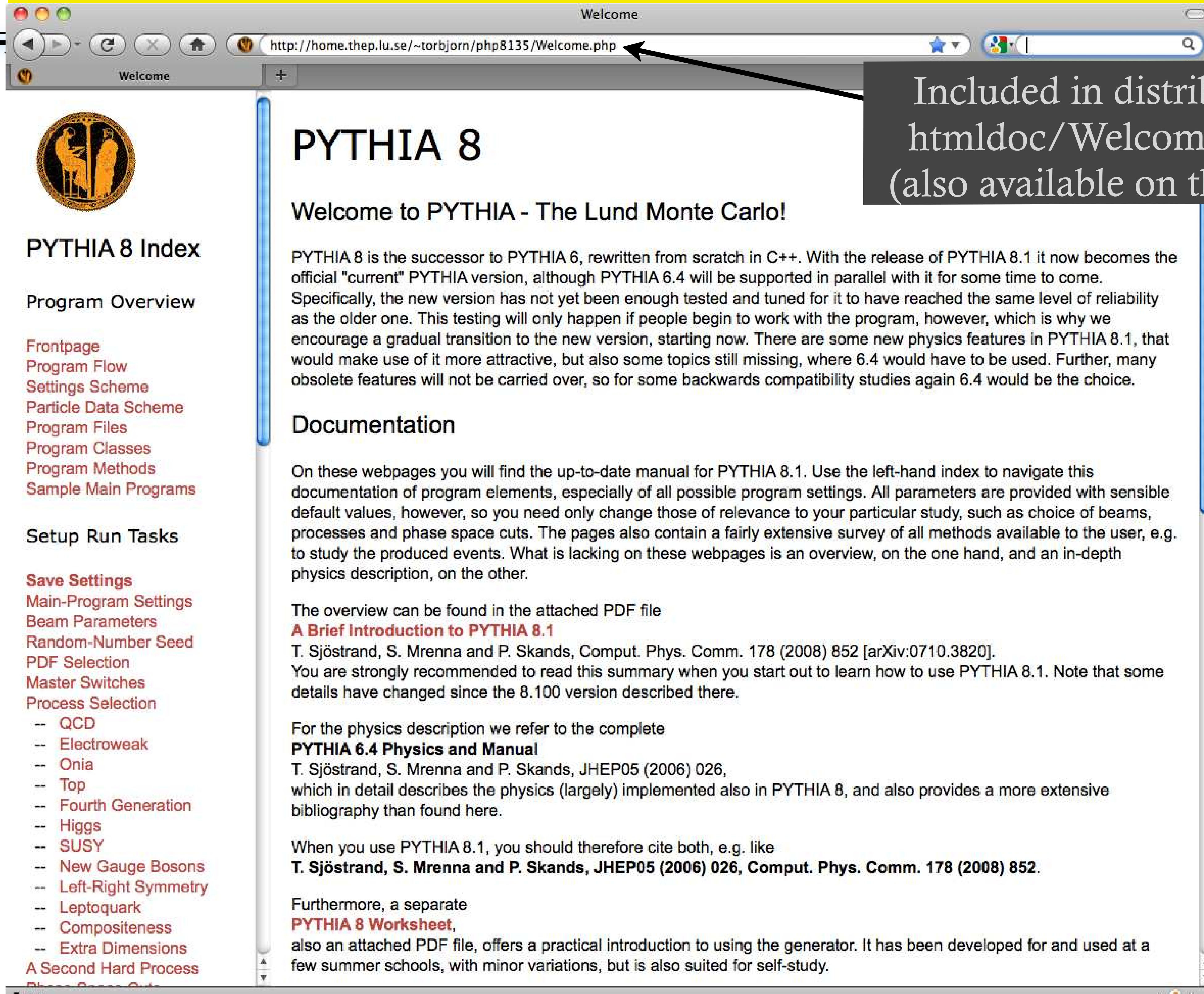
When you use PYTHIA 8.1, you should therefore cite both, e.g. like
T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026, Comput. Phys. Comm. 178 (2008) 852.

Furthermore, a separate
PYTHIA 8 Worksheet,
also an attached PDF file, offers a practical introduction to using the generator. It has been developed for and used at a few summer schools, with minor variations, but is also suited for self-study.

Done

Documentation

Included in distribution
htmldoc/Welcome.html
(also available on the web)



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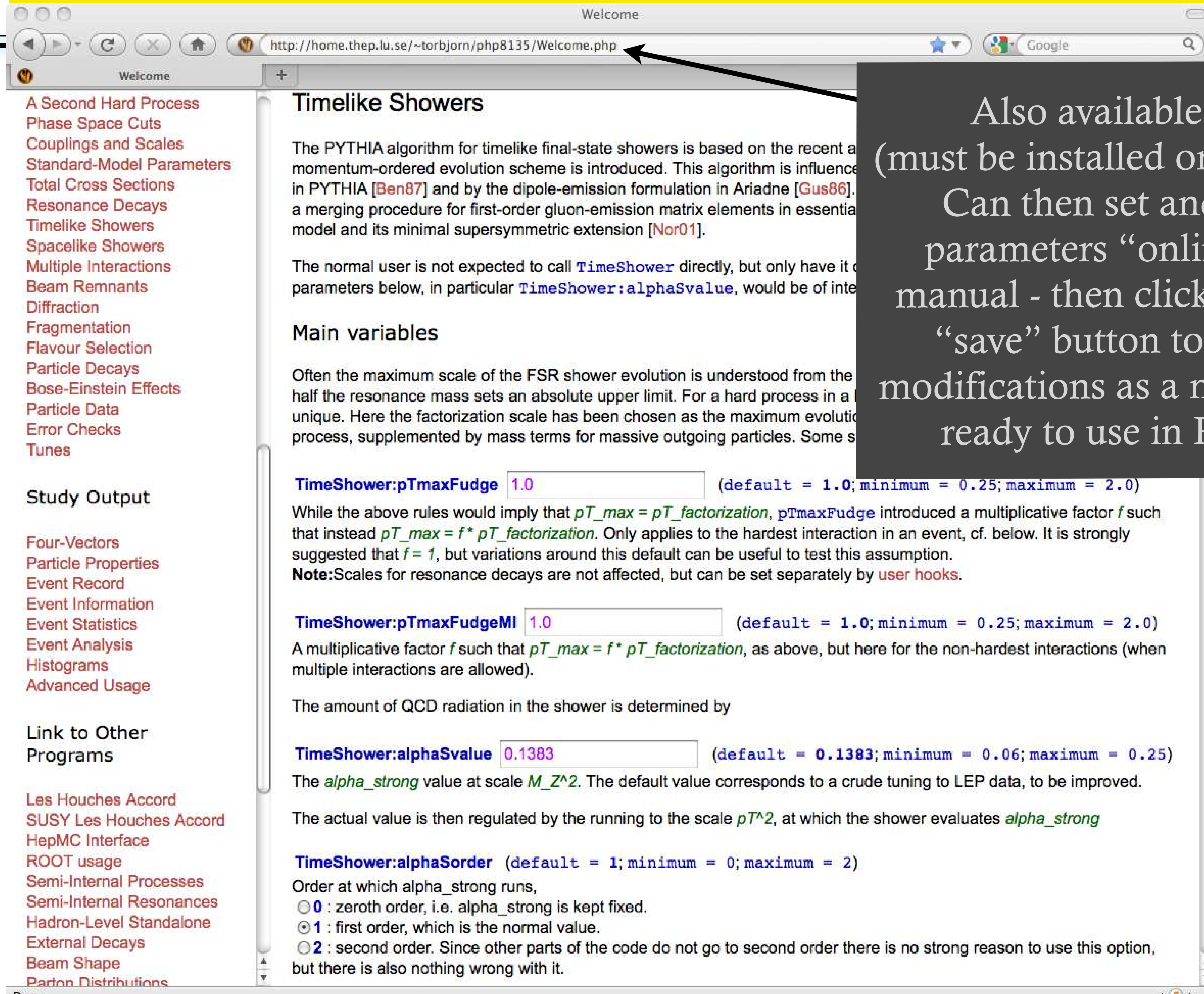

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A Second Hard Process
Phase Space Cuts
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Standard-Model Parameters
Total Cross Sections
Resonance Decays
Timelike Showers
Spacelike Showers
Multiple Interactions
Beam Remnants
Diffraction
Fragmentation
Flavour Selection
Particle Decays
Bose-Einstein Effects
Particle Data
Error Checks
Tunes

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SUSY Les Houches Accord
HepMC Interface
ROOT usage
Semi-Internal Processes
Semi-Internal Resonances
Hadron-Level Standalone
External Decays
Beam Shape
Parton Distributions

Timelike Showers

The PYTHIA algorithm for timelike final-state showers is based on the recent a
momentum-ordered evolution scheme is introduced. This algorithm is influence
in PYTHIA [Ben87] and by the dipole-emission formulation in Ariadne [Gus86].
a merging procedure for first-order gluon-emission matrix elements in essentia
model and its minimal supersymmetric extension [Nor01].

The normal user is not expected to call `TimeShower` directly, but only have it
parameters below, in particular `TimeShower:alphaSvalue`, would be of inte

Main variables

Often the maximum scale of the FSR shower evolution is understood from the
half the resonance mass sets an absolute upper limit. For a hard process in a
unique. Here the factorization scale has been chosen as the maximum evoluti
process, supplemented by mass terms for massive outgoing particles. Some s

TimeShower:pTmaxFudge 1.0 (`default = 1.0; minimum = 0.25; maximum = 2.0`)
While the above rules would imply that *pT_max = pT_factorization*, `pTmaxFudge` introduced a multiplicative factor *f* such that instead *pT_max = f * pT_factorization*. Only applies to the hardest interaction in an event, cf. below. It is strongly suggested that *f = 1*, but variations around this default can be useful to test this assumption.
Note: Scales for resonance decays are not affected, but can be set separately by user hooks.

TimeShower:pTmaxFudgeMI 1.0 (`default = 1.0; minimum = 0.25; maximum = 2.0`)
A multiplicative factor *f* such that *pT_max = f * pT_factorization*, as above, but here for the non-hardest interactions (when multiple interactions are allowed).

The amount of QCD radiation in the shower is determined by

TimeShower:alphaSvalue 0.1383 (`default = 0.1383; minimum = 0.06; maximum = 0.25`)
The *alpha_strong* value at scale *M_Z^2*. The default value corresponds to a crude tuning to LEP data, to be improved.

The actual value is then regulated by the running to the scale *pT^2*, at which the shower evaluates *alpha_strong*

TimeShower:alphaSorder (`default = 1; minimum = 0; maximum = 2`)
Order at which alpha_strong runs,
- **0** : zeroth order, i.e. alpha_strong is kept fixed.
- **1** : first order, which is the normal value.
- **2** : second order. Since other parts of the code do not go to second order there is no strong reason to use this option, but there is also nothing wrong with it.

Done

Also available as php
(must be installed on web server)
Can then set and change parameters “online” in the manual - then click the special “save” button to store the modifications as a new card file, ready to use in PYTHIA

Documentation

Welcome

http://home.thep.lu.se/~torbjorn/php8135/Welcome.php

Contents of examples/ directory also documented here (and more on how to use each of the interfaces)

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Sample Main Programs

Descriptions of available classes, methods and settings are all very good and u… to be able to fine-tune your runs to the task at hand. To get going, however, no… study. This is what is provided in the `examples` subdirectory, along with instru…

- `main01.cc` : a simple study of the charged multiplicity for jet events at t…
- `main02.cc` : a simple study of the *pT* spectrum of Z bosons at the Tevatron. (Brief example fitting on one slide.)
- `main03.cc` : a simple single-particle analysis of jet events, where input is set by `main03.cmnd` "cards file".
- `main04.cc` : a simple study of several different kinds of events, with the choice to be made in the `main04.cmnd` "cards file".
- `main05.cc` : generation of QCD jet events at the LHC, with jet analysis using the `CellJet` cone-jet finder.
- `main06.cc` : tests of cross sections for elastic and diffractive topologies, using `main06.cmnd` to pick process.
- `main07.cc` : tests of cross sections for minimum-bias events, using `main07.cmnd` to pick options.
- `main08.cc` : generation of the QCD jet cross section by splitting the run into subruns, each in its own *pT* bin, and adding the results properly reweighted. Two options, with limits set either in the main program or by subrun specification in the `main08.cmnd` file.
- `main09.cc` : generation of LEP1 hadronic events, i.e. *e^+e^- -> gamma*/Z^0 -> q qbar*, with charged multiplicity, sphericity, thrust and jet analysis.
- `main10.cc` : illustration how userHooks can be used interact directly with the event-generation process.
- `main11.cc` : generation of two predetermined hard interactions in each event.
- `main12.cc` : a study of top events, fed in from the Les Houches Event File `ttbar.lhe`, here generated by PYTHIA 6.4. This file currently only contains 100 events so as not to make the distributed PYTHIA package too big, and so serves mainly as a demonstration of the principles involved.
- `main13.cc` : a more sophisticated variant of `main12.cc`, where two Les Houches Event Files (`ttbar.lhe` and `ttbar2.lhe`) successively are used as input. Also illustrating some other aspects, like the capability to mix in internally generated events.
- `main14.cc` : a systematic comparison of several cross section values with their corresponding values in PYTHIA 6.4, the latter available as a table in the code.
- `main15.cc` : loop over several tries, either to redo B decays only or to redo the complete hadronization chain of an event. Since much of the generation process is only made once this is a way to increase efficiency.
- `main16.cc` : put all user analysis code into a class of its own, separate from the main program; provide the "cards file" name as a command-line argument.
- `main17.cc` : collect the Pythia calls in a wrapper class, thereby simplifying the main program; provide the "cards file" name as a command-line argument.

Done

Summary & Outlook

PYTHIA 6

- Supported (bug fixes etc)
- But not actively developed (no new physics)

PYTHIA 8

- Started by Torbjorn, other authors now migrating
  - Actively developed and supported
- Core program ready and tuned
  - Extensive documentation and example programs
  - Problem with UE description under investigation
- Flexible structure with many user I/O possibilities
  - Steerable by cards
  - Built-in interfaces (e.g., LHEF, HepMC, FastJet, LHAPDF)
  - User hooks to veto events or modify cross sections (e.g., for matching with AlpGen, MadGraph, etc)
  - User derived classes (e.g., user processes, user resonance decays, user particle decays, even user parton showers) inheriting from the base Pythia classes