PYTHIA 8 Kickstart

P. Skands (CERN-TH)

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** (CERN)
- **Richard Corke** (Lund)
- **Stephen Mrenna** (FNAL)
- **Torbjorn Sjostrand** (Lund)
- **Peter Skands** (CERN)

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)

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

- **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

Perturbative Resonance Decays

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

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')*
- **Showers**
  - Transverse-momentum ordered ISR & FSR
  - Includes QCD and QED
  - Dipole-style recoils *(partly new)*
  - Improved high-$p_\perp$ shower behavior [R. Corke]
- **Matrix-Element Matching**
  - Automatic first-order matching for most gluon-emission processes in resonance decays, e.g.,:
    - $Z \to qq \to qqg$,
    - $t \to bW \to bWg$,
    - $H \to bb \to bbg$,
    - …
  - Automatic first-order matching for internal $2 \to 1$ color-singlet processes, e.g.:
    - $pp \to Z/W/Z'/W'$+jet
    - $pp \to H$+jet
    - More to come …
  - Interface to AlpGen, MadGraph, … via Les Houches Accords

Physics (3/3)

- **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 $p_\perp$
    - Option: parton rescattering **[R. Corke]**
  - Beam remnants
    - String junctions → variable amount of baryon transport
  - Tuned to Tevatron Min-Bias
  - Improved model of diffraction
    - Diffractive jet production **[S. Navin]**
- **Hadronization**
  - String fragmentation
    - Lund symmetric fragmentation function for (u,d,s) + Bowler modification for heavy quarks (c,b) [+ option for Peterson]
  - 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)*
- **Output**
  - Interface to HEPMC included

Key differences between PYTHIA 8 and PYTHIA 6

- **New features, not found in 6.4**
  - Up-to-date PDFs
  - Up-to-date PDG decay data
  - Improved 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
    - Allow 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

- **Old features definitely removed**
  - Independent fragmentation
  - Mass-ordered showers

- **Features omitted so far**
  - ep, γp and $\gamma\gamma$ beams
  - Some matrix elements, in particular Technicolor, partly SUSY

SUSY with NMFV and/or CPV *(not fully validated)*
Large Extra Dimensions, Unparticles
Hidden Valley scenario with hidden radiation

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 (only static switched on by default)
  - 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

- **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/
========================
 28M  pythia8135
```

  - Executables

```
2.3M  examples/main01.exe
```

    - Typical size of standalone executable.
    - Bigger if linked to external packages
- **Memory Usage**

```
~ 10M standalone
```

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

Speed and Optimization

(on 3GHz processor)

- **Compiling PYTHIA 8** (from scratch)

```
real    1m41.053s
user    1m23.870s
sys 0m6.944s
```

- **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

- **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 in `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 How to Change Parameters**
  - Directly in your code: `pythia.readString("parameter = value");`
  - OR: collect any number of such strings in a file (e.g., `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

Frontpage
Program Flow
Settings Scheme
Particle Data Scheme
Program Files
Program Classes
Program Methods
Sample Main Programs

Setup Run Tasks

Save Settings
Main-Program Settings
Beam Parameters
Random-Number Seed
PDF Selection
Master Switches
Process Selection
-- QCD
-- Electroweak
-- Onia
-- 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

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

Included in package:
…/pythia8135/htmldoc/Welcome.html
(also available on the web)

Documentation

Welcome

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

Welcome

A Second Hard Process
Phase Space Cuts
Couplings and Scales
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

Study Output

Four-Vectors
Particle Properties
Event Record
Event Information
Event Statistics
Event Analysis
Histograms
Advanced Usage

Link to Other Programs

Les Houches Accord
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
momentum-ordered evolution scheme is introduced. This algorithm
in PYTHIA [Ben87] and by the dipole-emission formulation in Ariad
a merging procedure for first-order gluon-emission matrix elements
model and its minimal supersymmetric extension [Nor01].

The normal user is not expected to call `TimeShower` directly, but c
parameters below, in particular `TimeShower:alphaSvalue`, wou

Main variables

Often the maximum scale of the FSR shower evolution is understo
half the resonance mass sets an absolute upper limit. For a hard p
unique. Here the factorization scale has been chosen as the maxin
process, supplemented by mass terms for massive outgoing partic

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

Sample Main Programs

Welcome

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

Google

Welcome

PYTHIA 8 Index

Program Overview

Frontpage
Program Flow
Settings Scheme
Particle Data Scheme
Program Files
Program Classes
Program Methods
Sample Main Programs

Setup Run Tasks

Save Settings
Main-Program Settings
Beam Parameters
Random-Number Seed
PDF Selection
Master Switches
Process Selection
-- QCD
-- Electroweak
-- Onia
-- Top
-- Fourth Generation
-- Higgs
-- SUSY
-- New Gauge Bosons
-- Left-Right Symmetry
-- Leptoquark
-- Compositeness
-- Extra Dimensions
A Second Hard Process
Phase Space Cuts

Sample Main Programs

Descriptions of available classes, methods and settings are all very good and
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 Teva
- `main03.cc` : a simple single-particle analysis of jet events, where input
- `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

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

Tuning

3 Kinds of Tuning

1. Fragmentation Tuning

Non-perturbative: hadronization modeling & parameters

Perturbative: jet radiation, jet broadening, jet structure

2. Initial-State Tuning

Non-perturbative: PDFs, primordial k_T

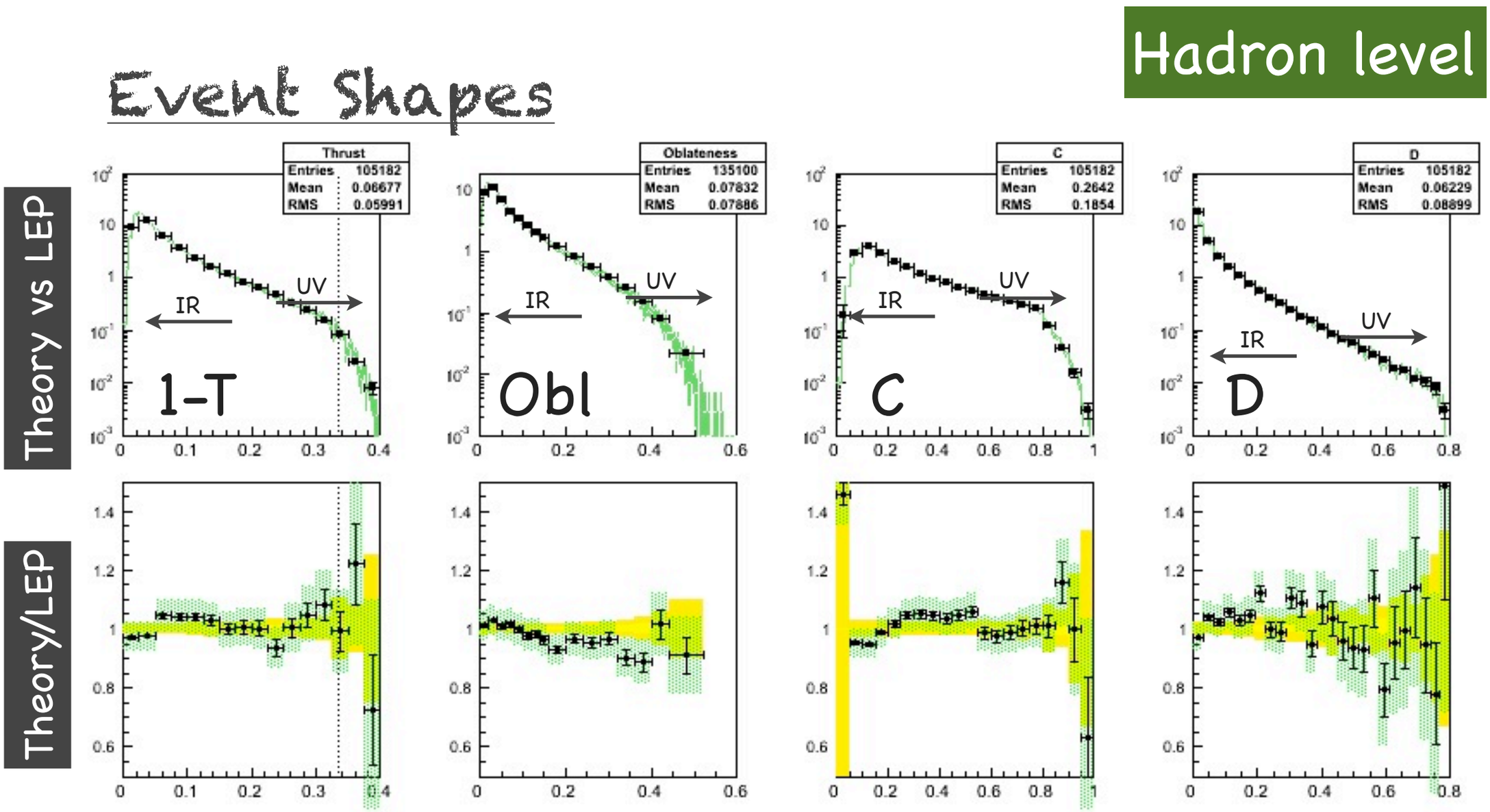
Perturbative: initial-state radiation, initial-final interference

3. Underlying-Event & Min-Bias Tuning

Non-perturbative: Multi-parton PDFs, Color (re)connections, collective effects, impact parameter dependence, …

Perturbative: Multi-parton interactions, rescattering

LEP Event Shapes

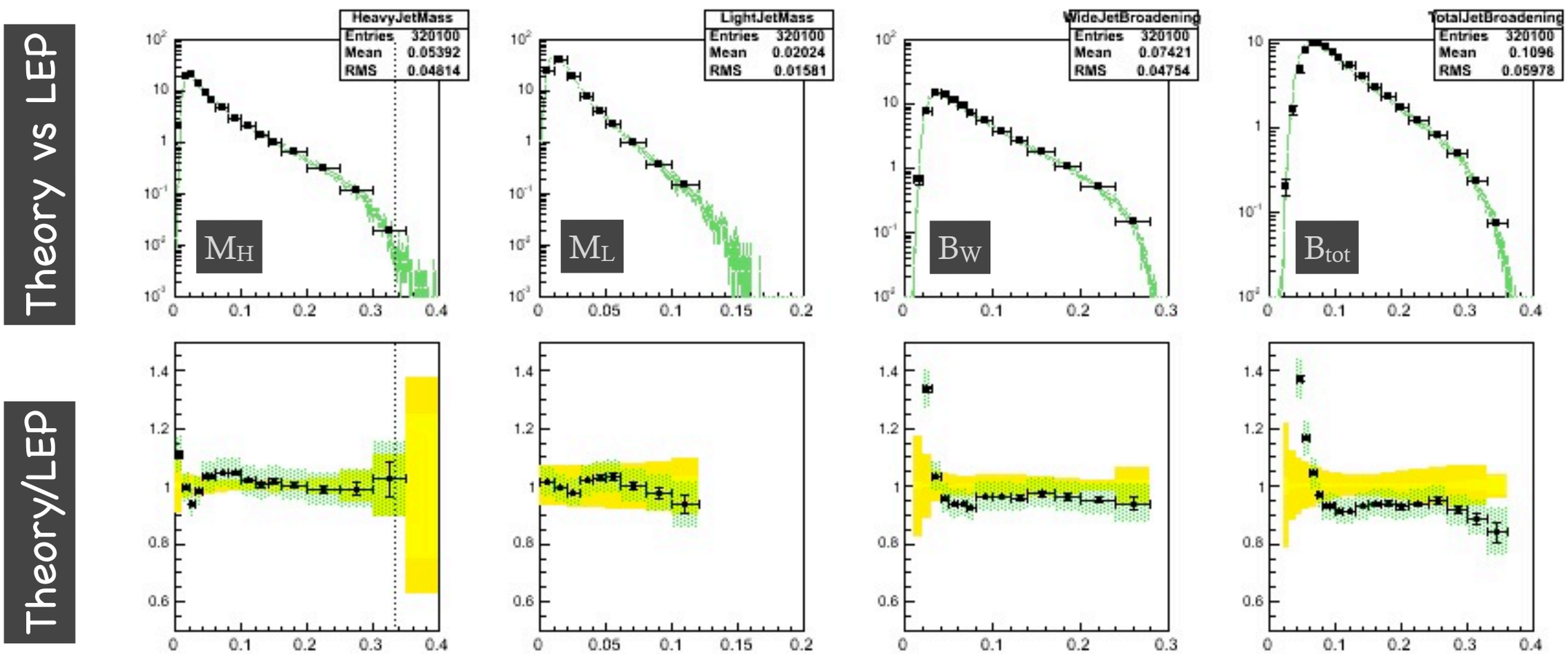


(default PYTHIA 8.135)

More Event Shapes

Jet Masses and Jet Broadening

Hadron level



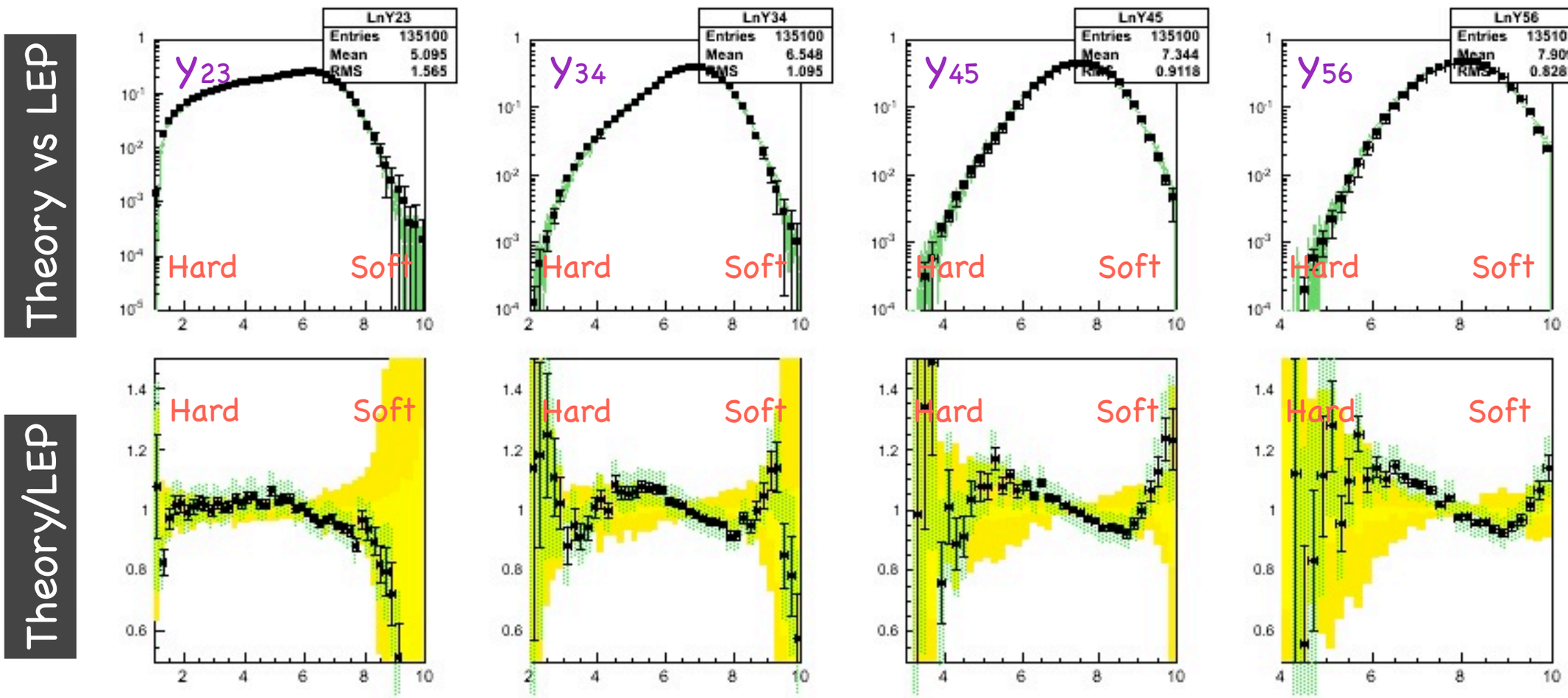
Jet Rates

At E_{vis} = 91 GeV
$y=2 \rightarrow k_T \approx 33$ GeV
$y=4 \rightarrow k_T \approx 12$ GeV
$y=6 \rightarrow k_T \approx 4.5$ GeV
$y=8 \rightarrow k_T \approx 1.6$ GeV
$y=10 \rightarrow k_T \approx 0.6$ GeV

Jet Resolution

Hadron level

E.g., $y_{23} = k_T^2 / E_{vis}^2$ = scale where event goes from having 2 to 3 jets



(default PYTHIA 8.135)

Tuning in the Infrared

1. Fragmentation Tuning

Constrain incalculable model parameters

Good model → good fit. Bad model → bad fit → improve model

$P_s/P_{u,d}$

P_{Baryon}/P_{Meson}

Λ_{QCD}

IR α_s

Q_{cutoff}

$P_{vector}/3P_{scalar}$

$f(z,Q^2)$

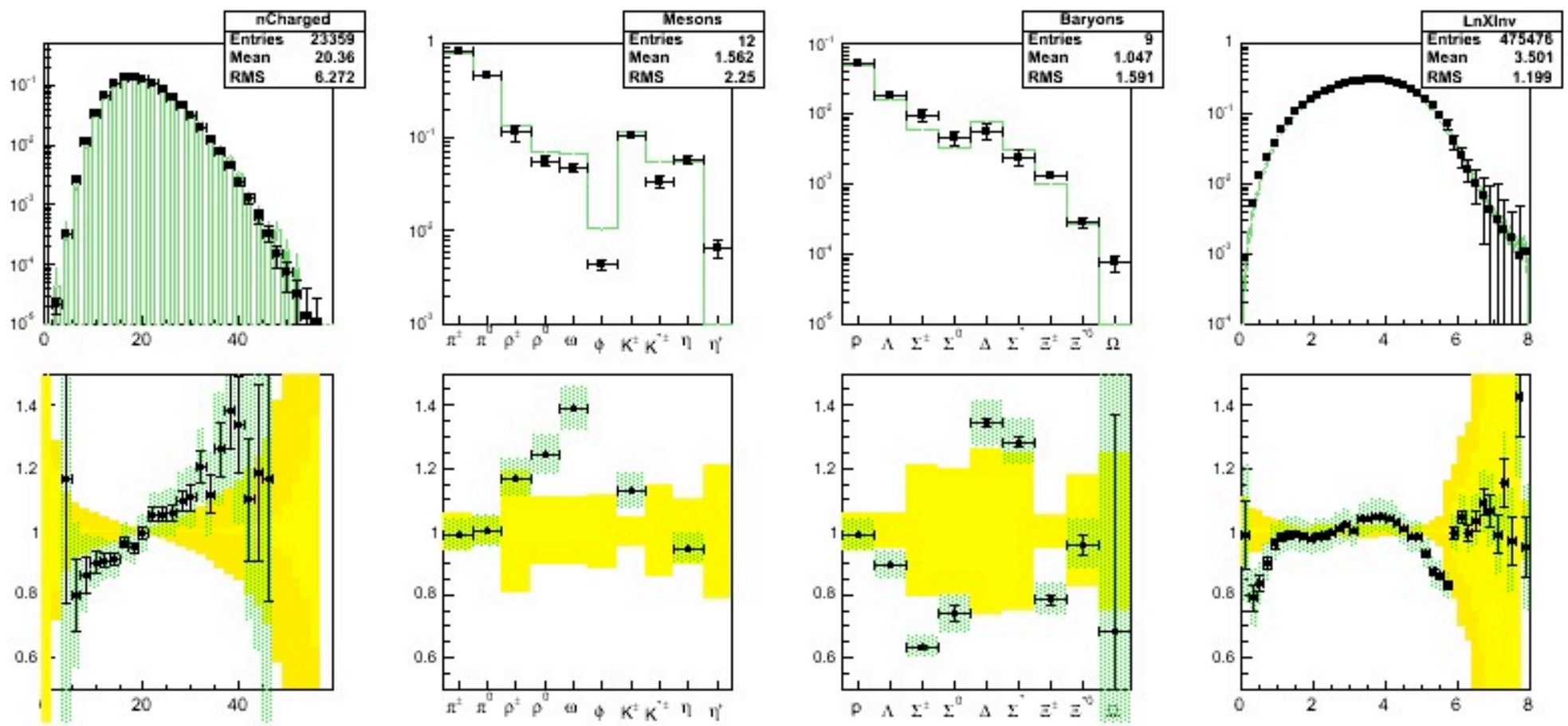
$p_{\perp F}$

η,η' suppression

$f_{c,b}(z,Q^2)$

Before

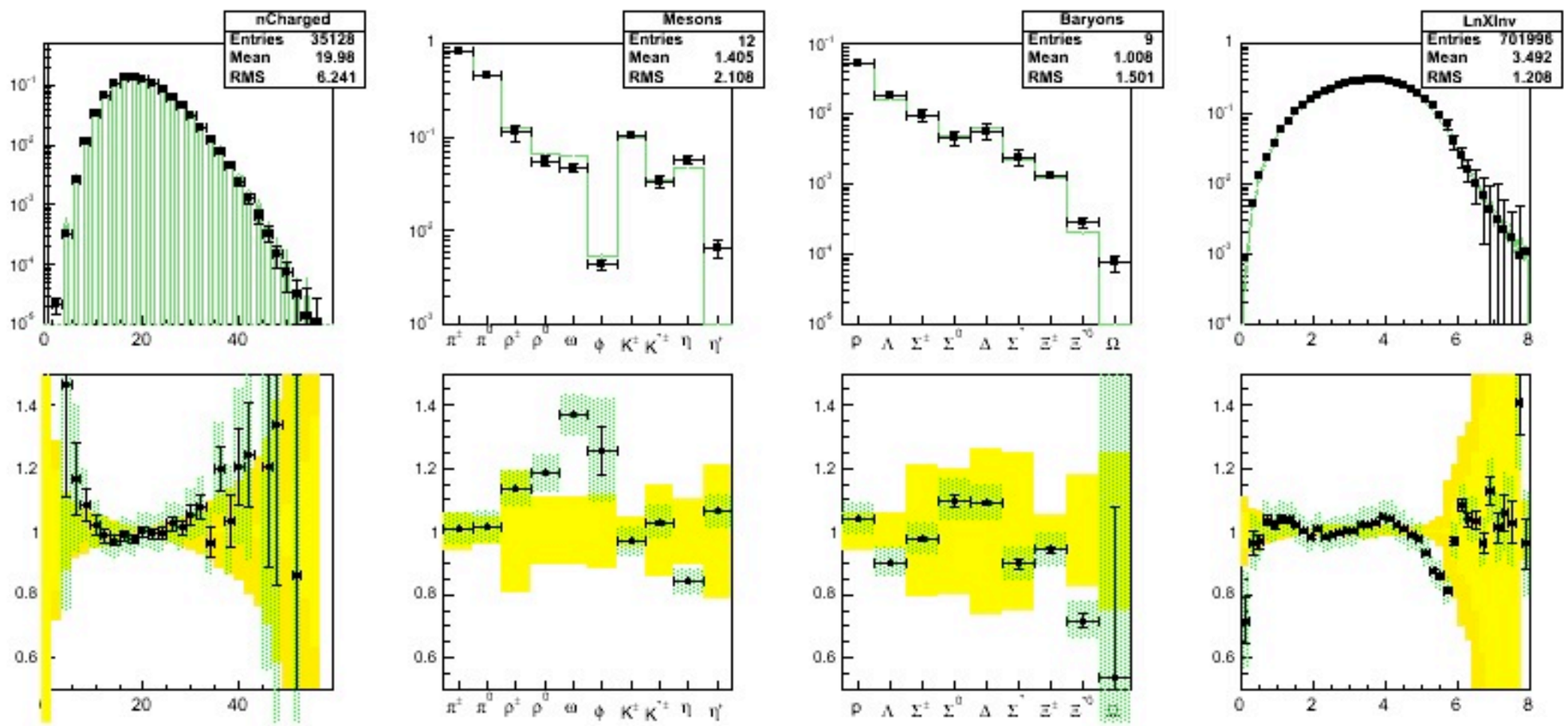
PYTHIA 8.100



N_{ch} Mesons Baryons Ln(1/x)

After

PYTHIA 8.135

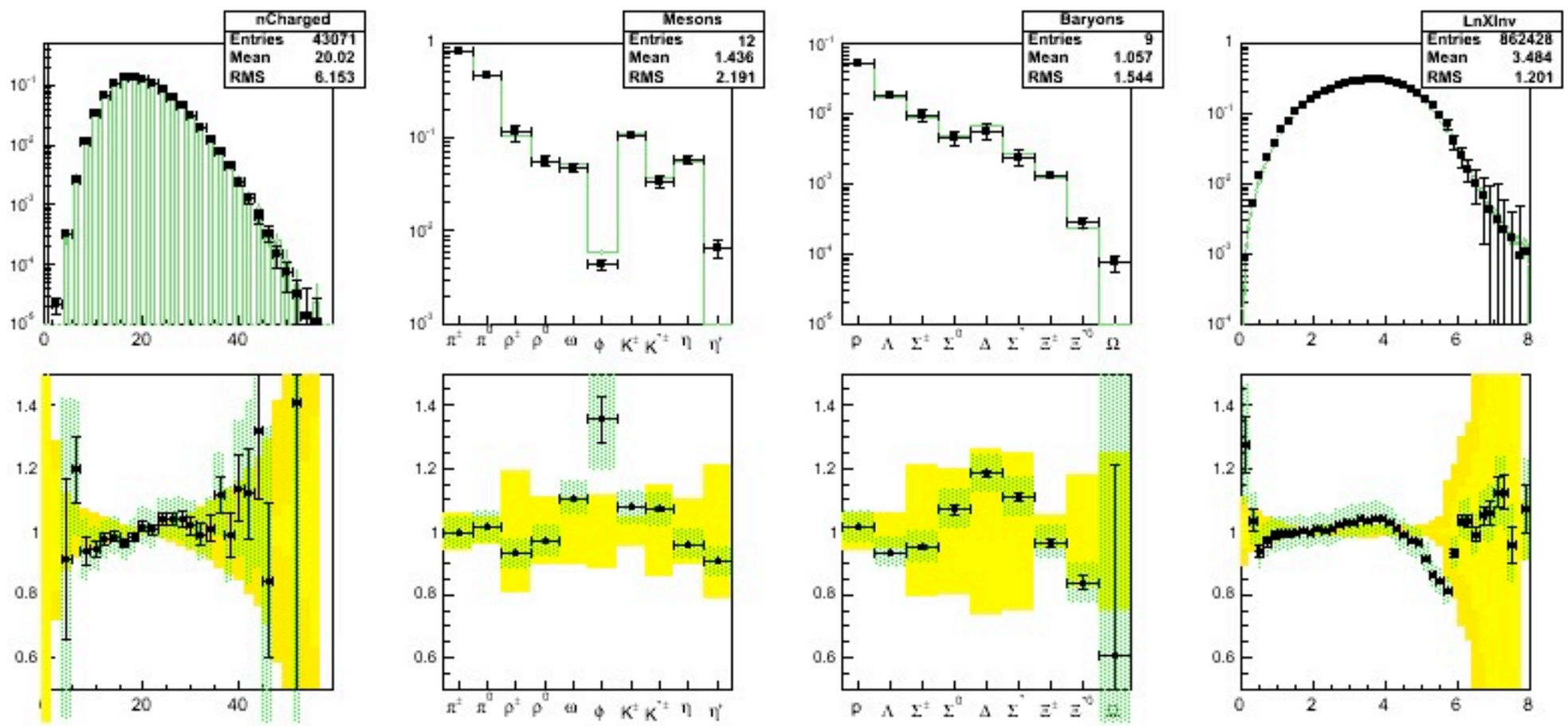


N_{ch} Mesons Baryons Ln(1/x)

(with VINCIA antenna shower)

PYTHIA 8.135 + VINCIA 1.023

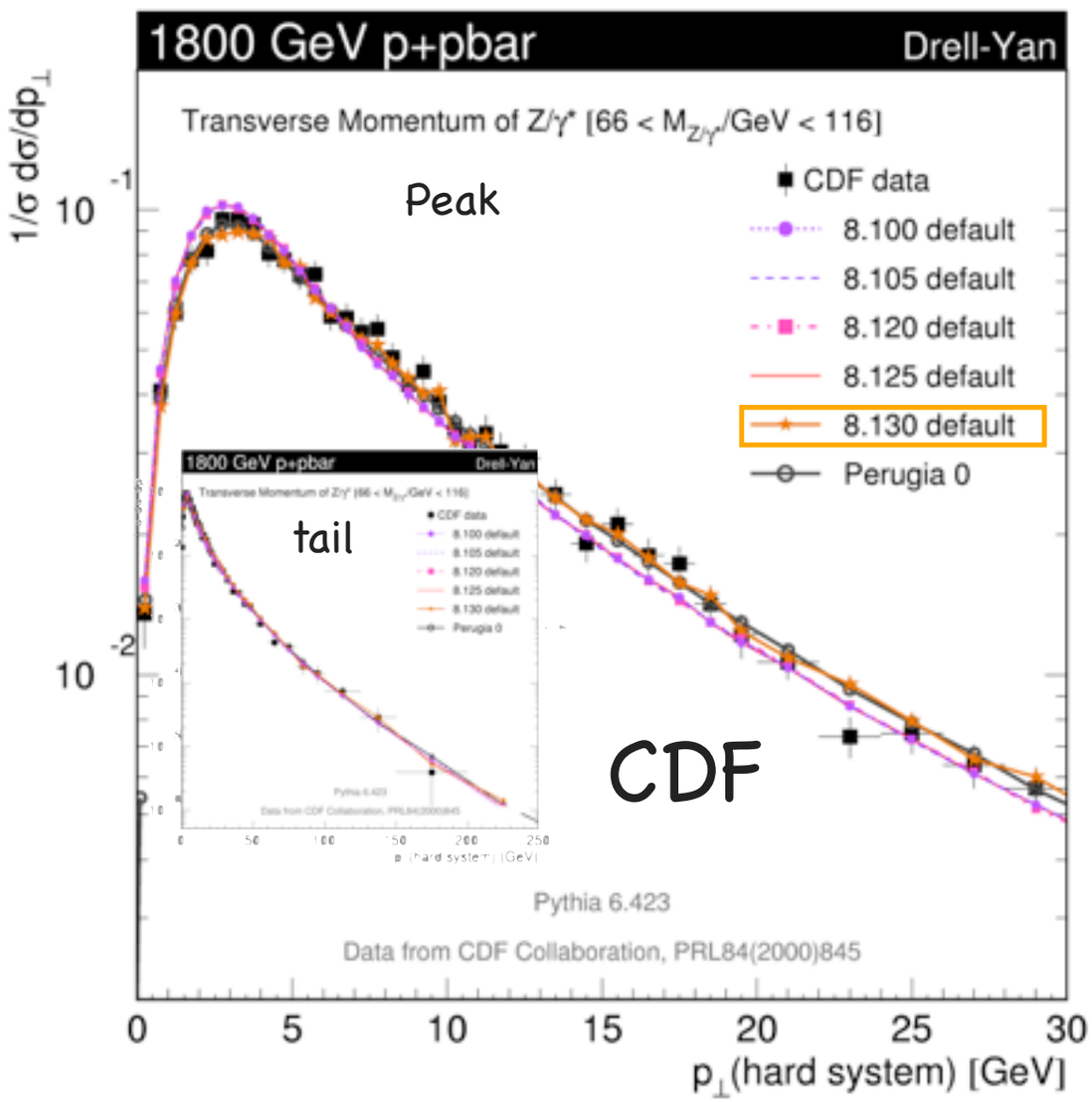
(Different shower,
same hadronization model)

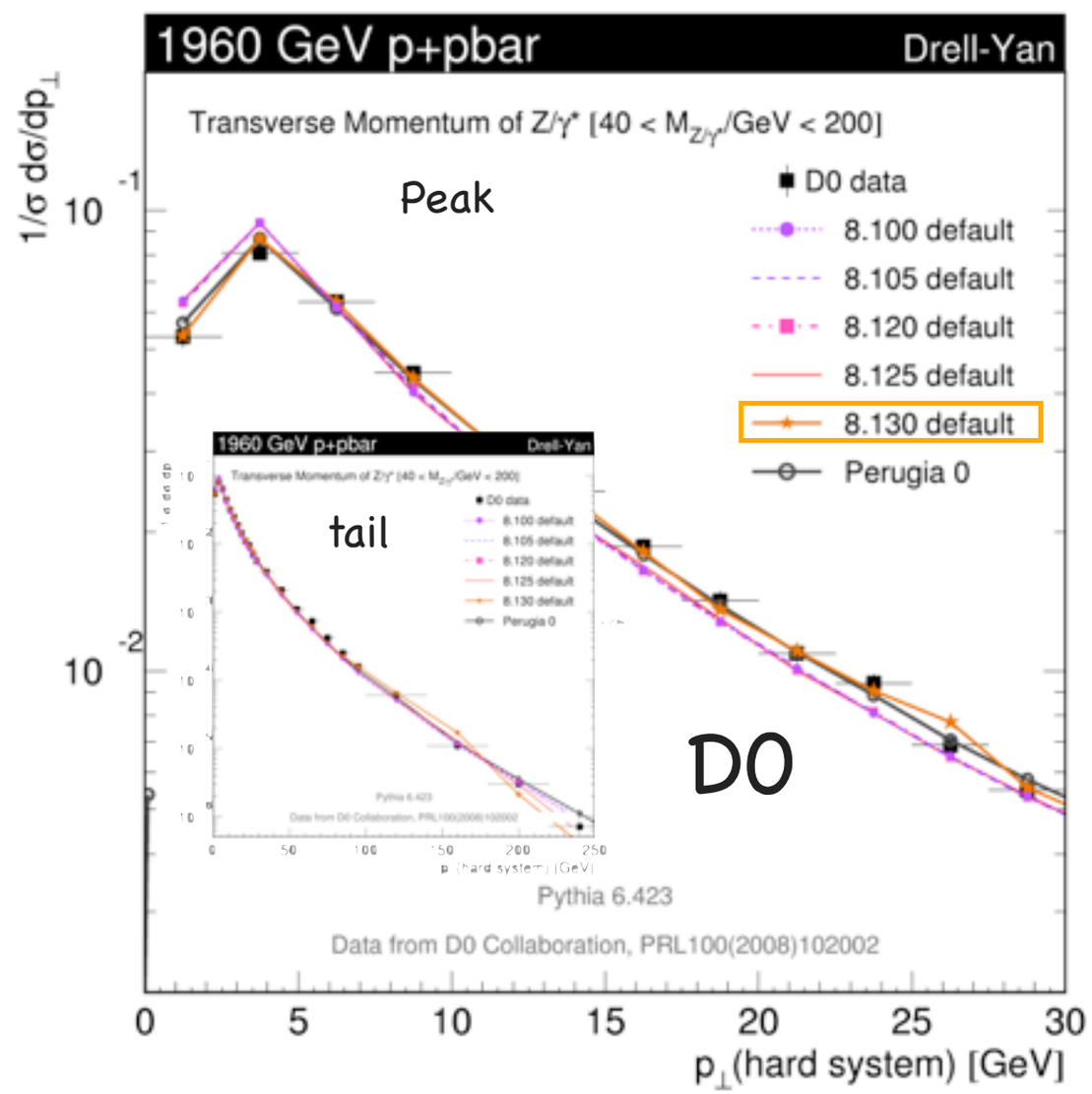


N_{ch} Mesons Baryons Ln(1/x)

Initial-State Radiation

Drell-Yan p_T distribution

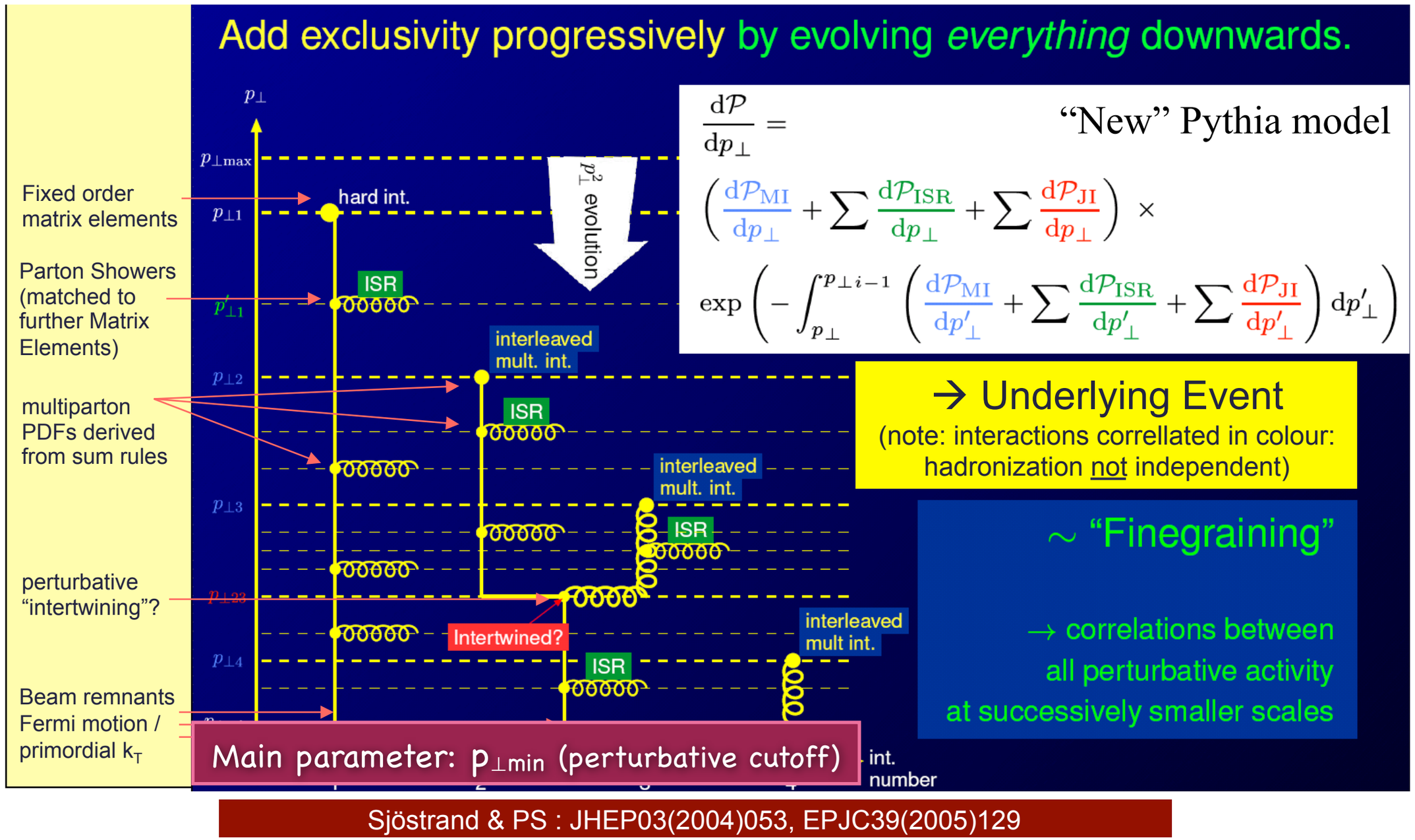




Tuning for Min-Bias and Underlying-Event

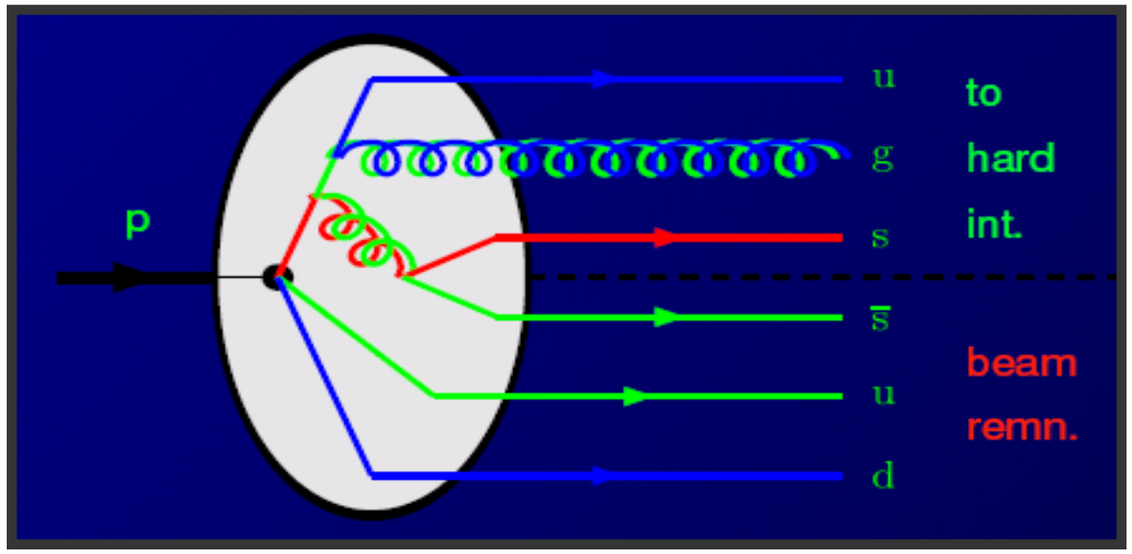
(+ some physics spillover)

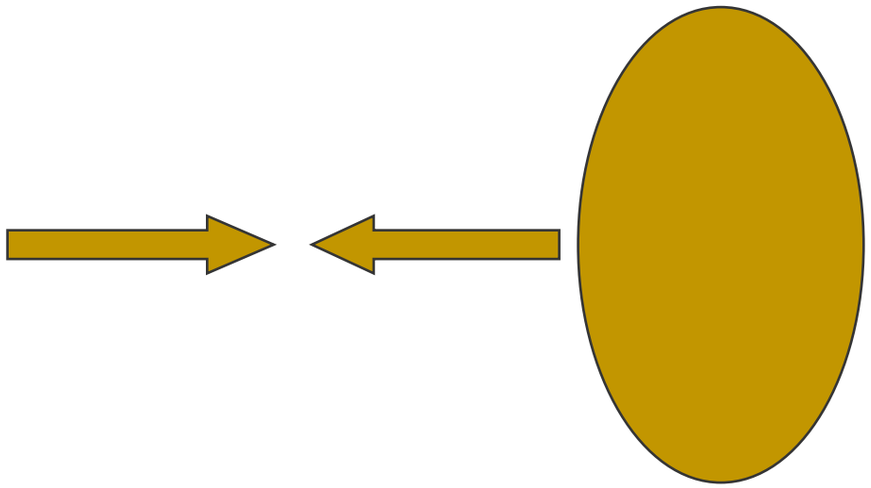
Interleaved Evolution



Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

Multi-Parton PDFs





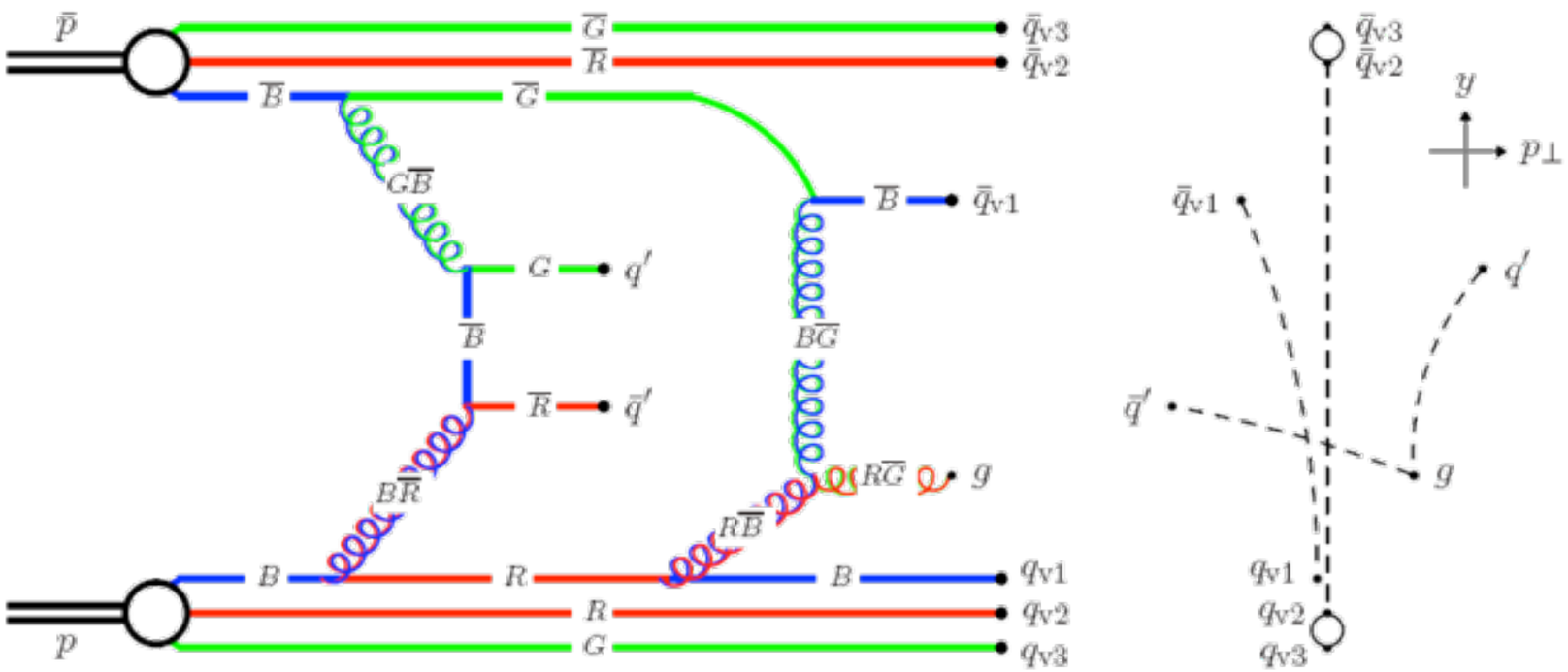
How are the initiators and remnant partons correllated?

- in impact parameter?
- in flavour?
- in x (longitudinal momentum)?
- in k_T (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

Spiky: large event-to-event fluctuations
Smooth: smaller fluctuations

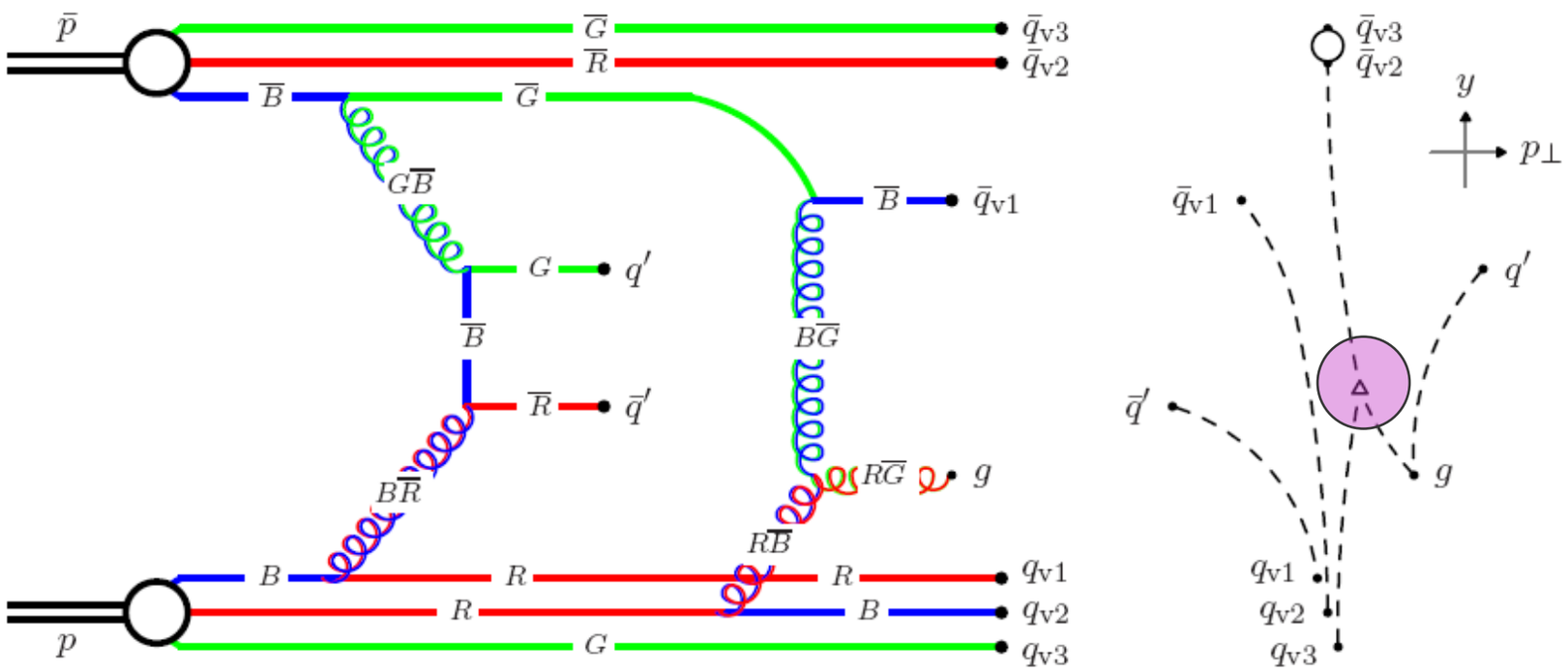
Colour and the UE

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions <u>crucially</u> depend on color space



Colour and the UE

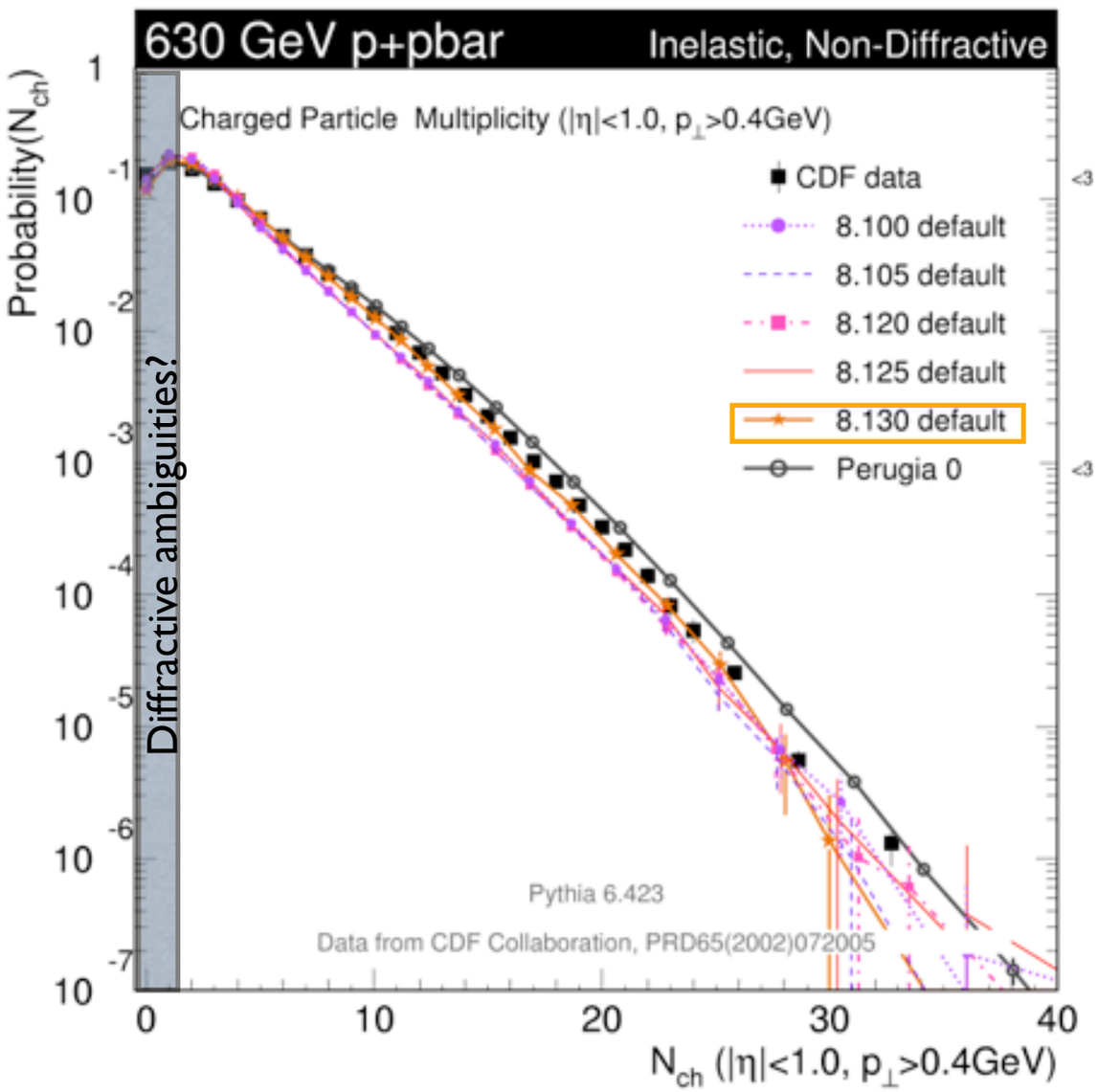
- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions <u>crucially</u> depend on color space

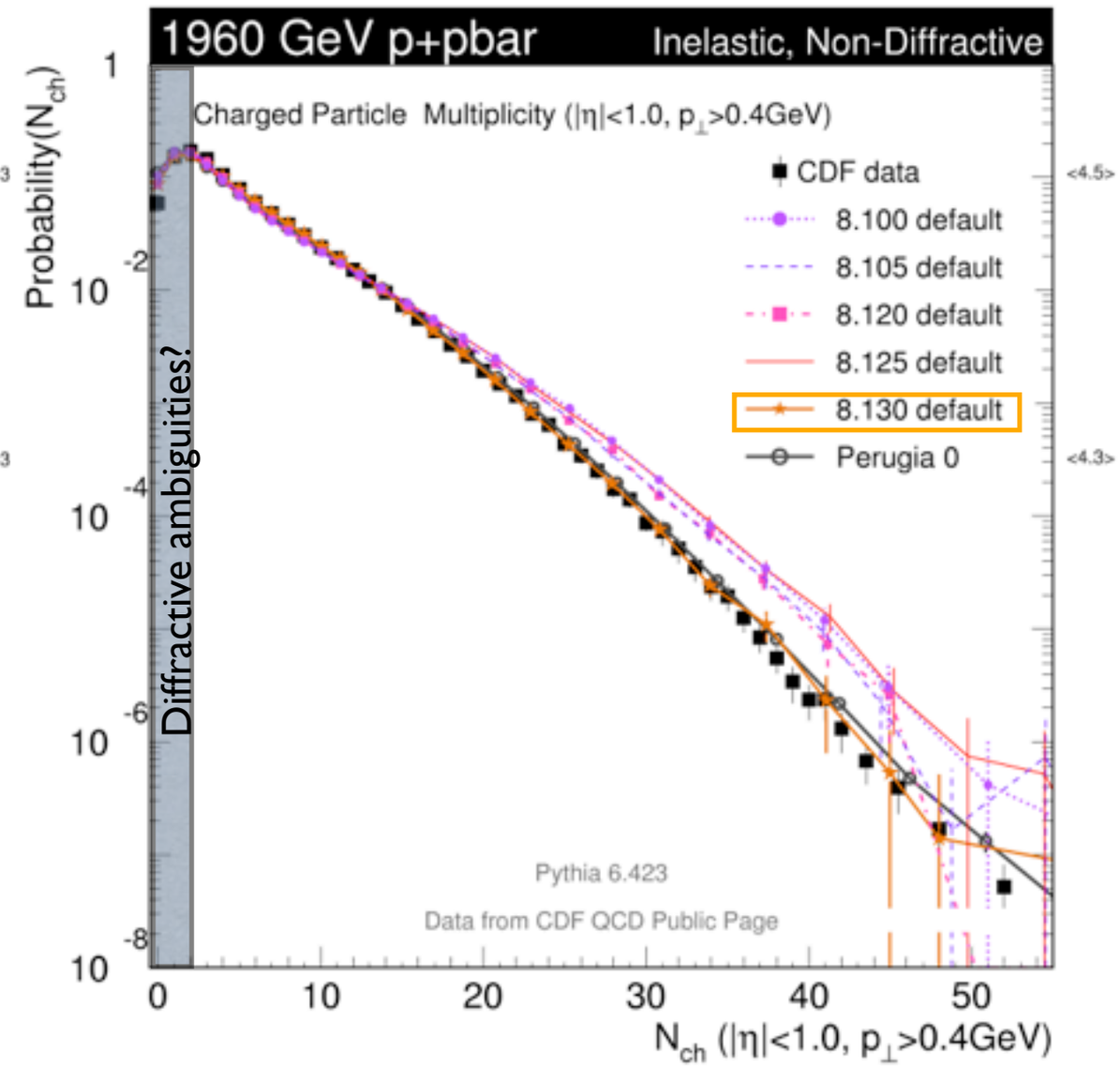


Note: this just color **connections**, then there may be color **reconnections** too

Minimum-Bias

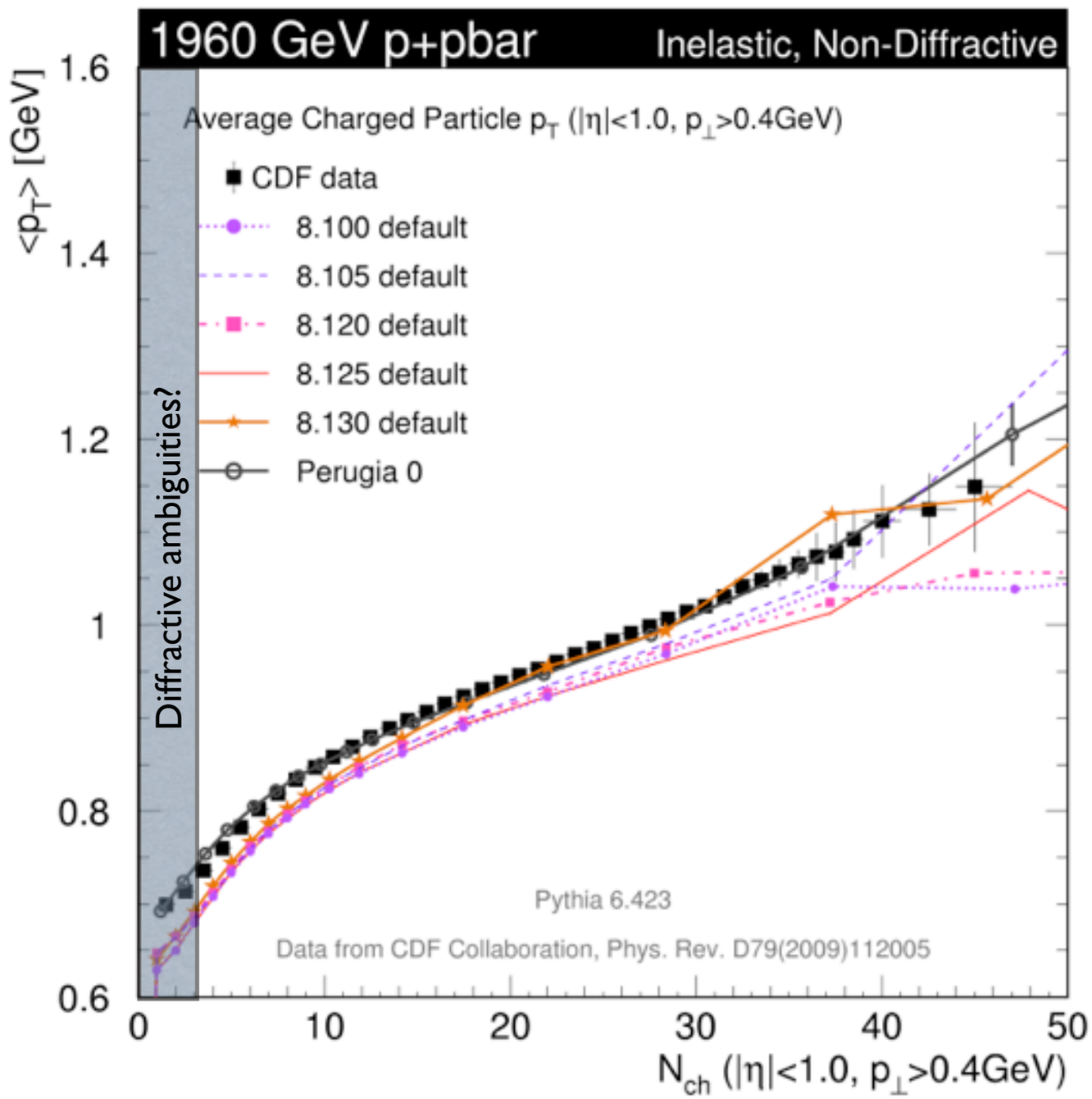
630 GeV **Multiplicity Distribution** 1960 GeV





Minimum-Bias

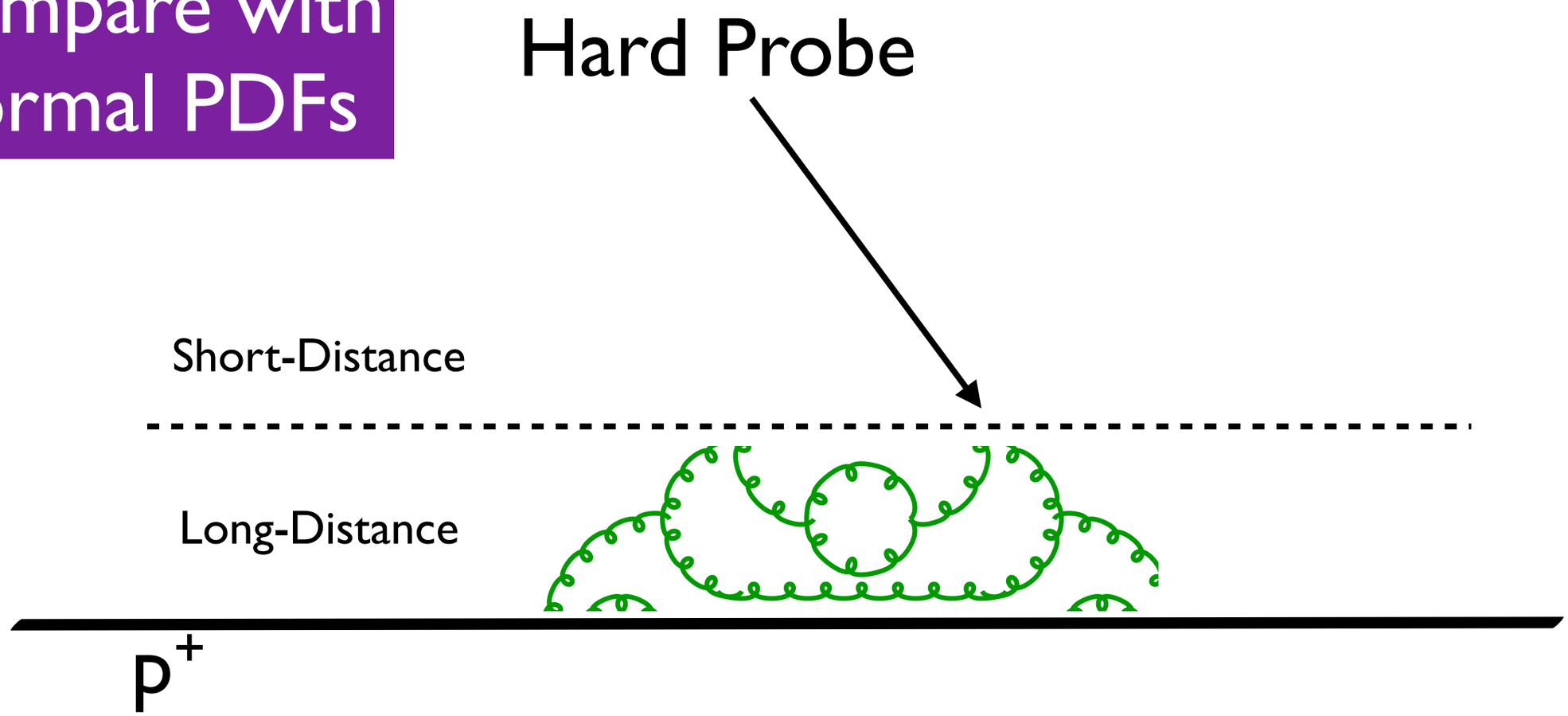
Average Track p_T vs Multiplicity



(+ Diffraction)

"Intuitive picture"

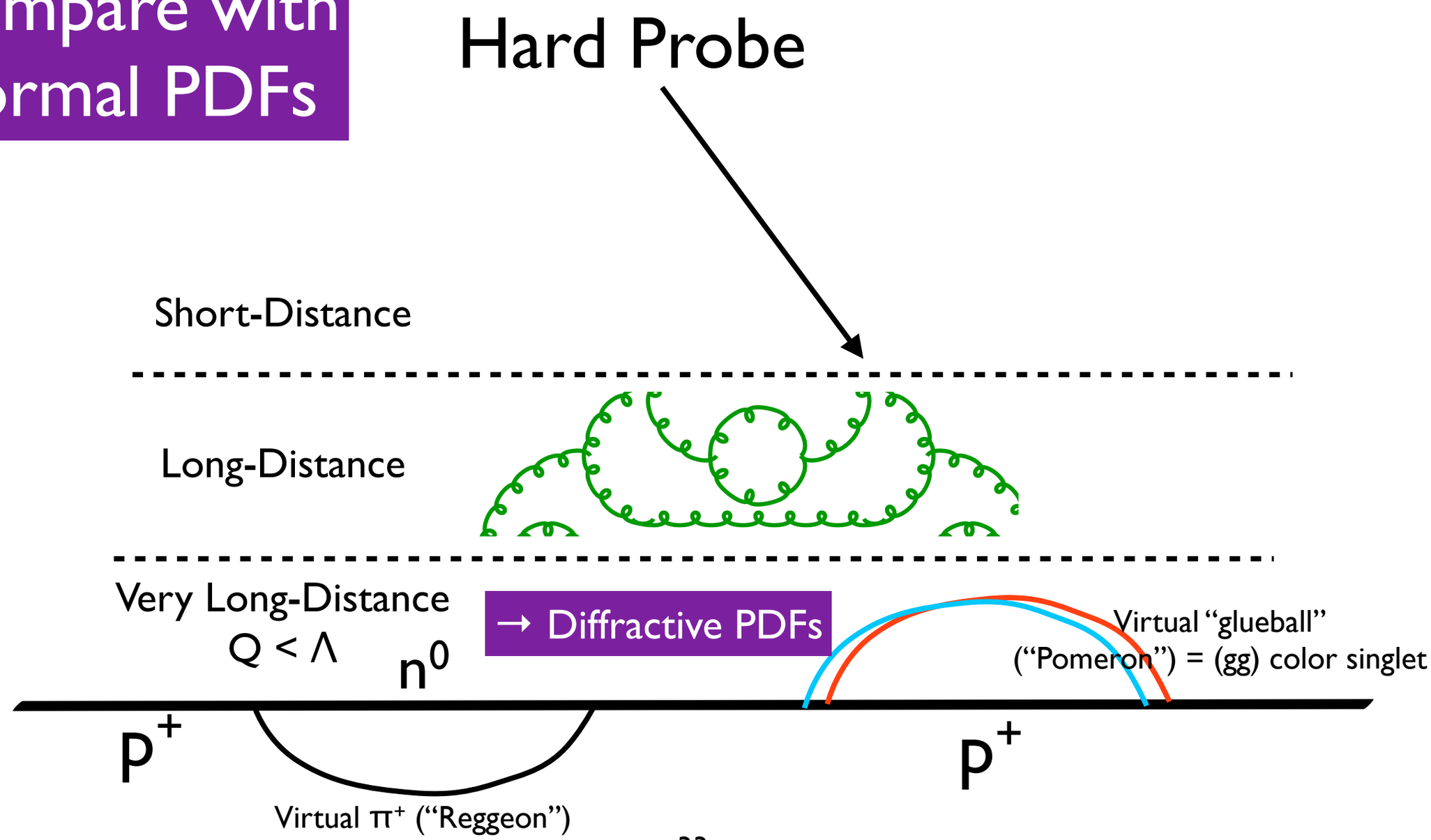
Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

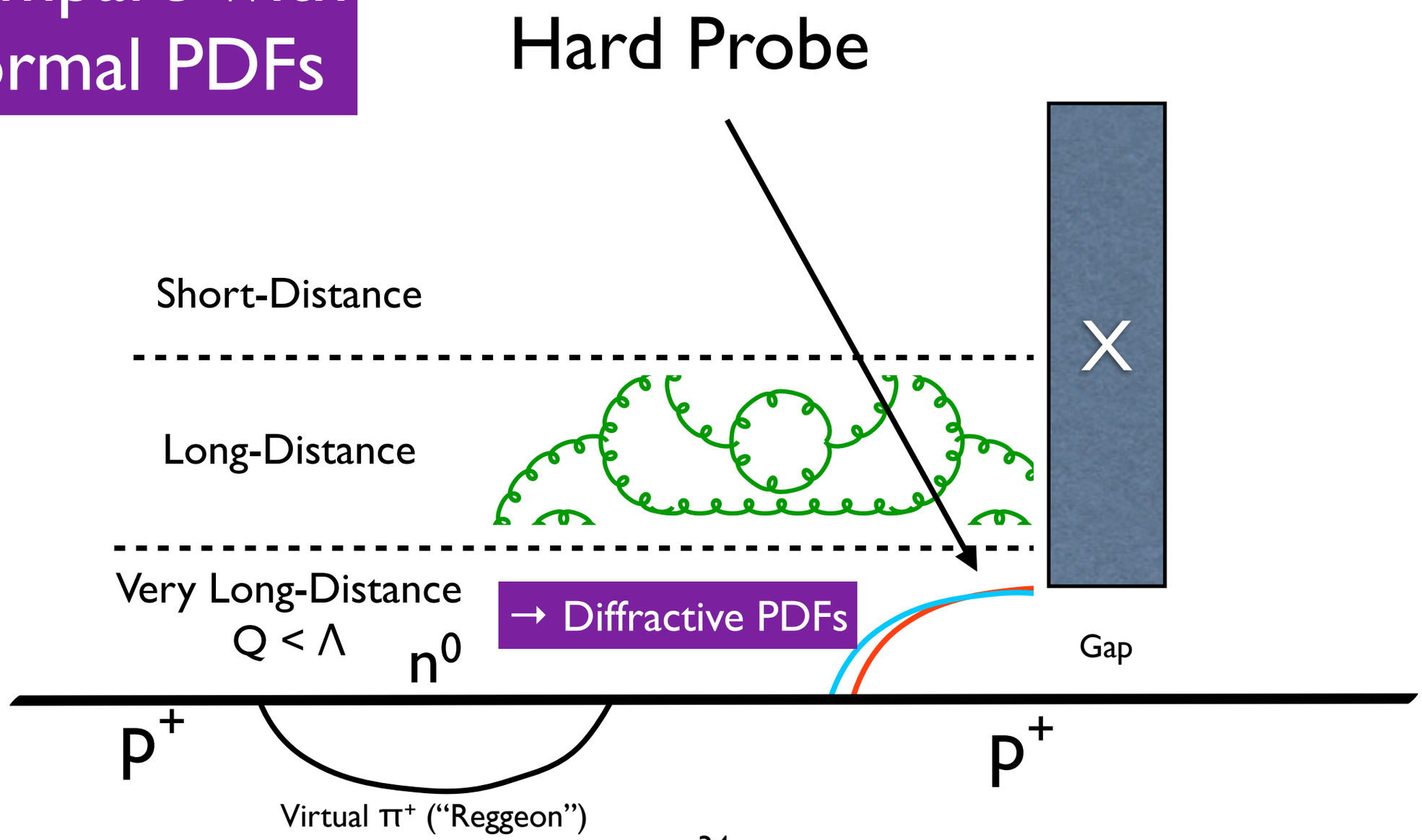
Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs



Diffraction in PYTHIA 8

S. Navin (MCnet) + T. Sjöstrand

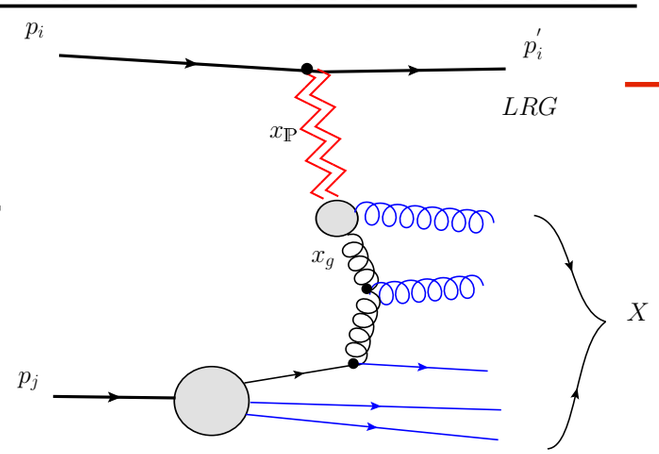
Diffractive Cross Section Formulæ:

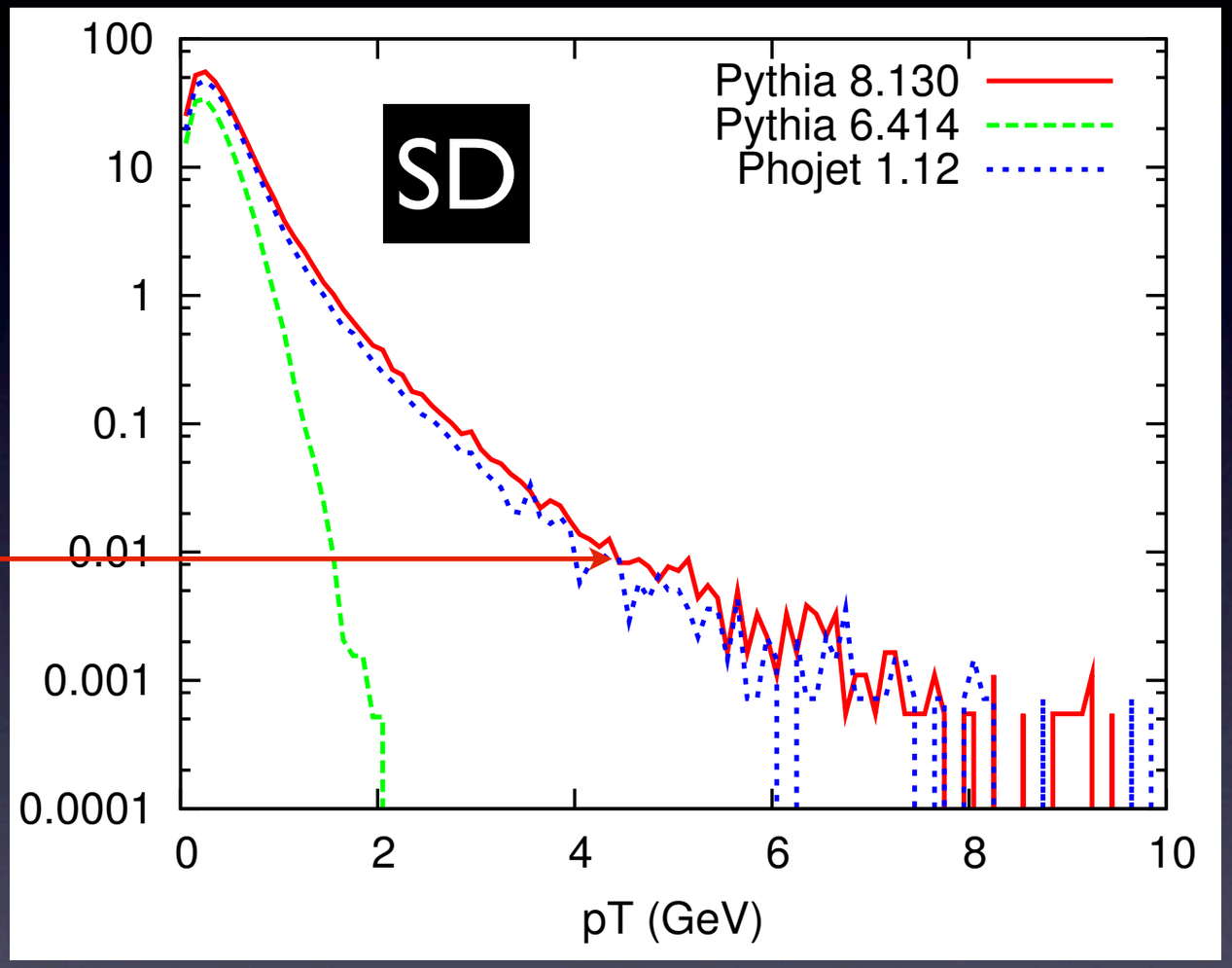
$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\ ,$$

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

Partonic Substructure in Pomeron:

Follows the approach of Pompyt



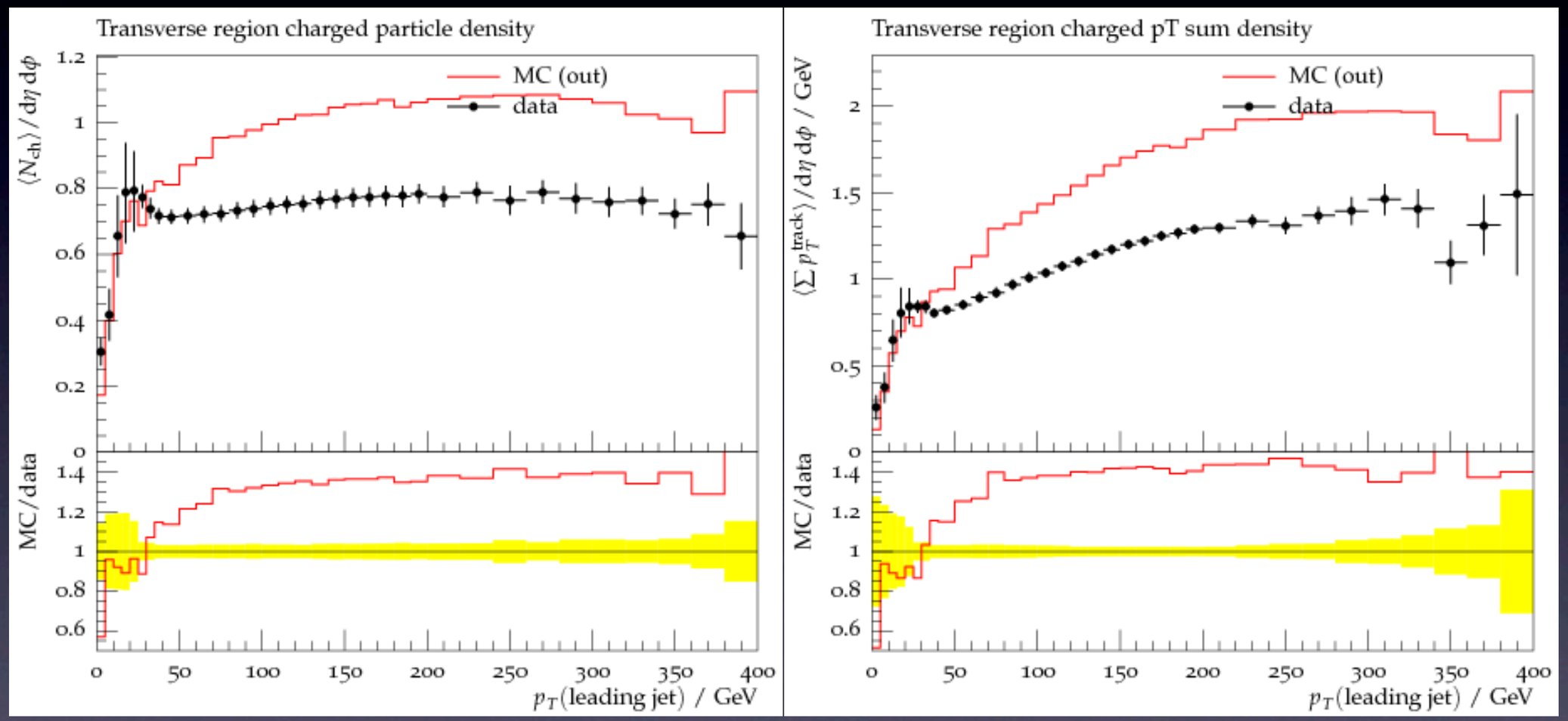


- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: new perturbative description used

Status: Supported and actively developed

The Snag!

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?

Summary & Outlook

PYTHIA 6

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

PYTHIA 8

Actively developed and supported (though check with your MC responsibles before mailing questions directly - there are just a few of us)

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, VINCIA) + 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

PYTHIA 8 Kickstart

Preparation for Pythia 8

- The code is entirely standalone. All you need is a C compiler
- Download the tarball from the Pythia 8 web site (you can also just type Pythia in google, but be careful to get PYTHIA 8, not 6)

http://home.thep.lu.se/~torbjorn/pythia8/pythia8135.tgz

  - Unpack it, move to the pythia8135/ directory
  - ./configure

    (open the README file if you want to know about possible fancy options you can use)
  - make

Examples to try

Move to the examples/ subdirectory

```
…/pythia8135/examples/
```

Compile the first example program, main01

```
make main01
./main01.exe
```

Familiarize yourselves with the event record it prints

(open the HTML manual in a browser, scroll down to "Study Output" and look at "particle properties", "event record", and any other topics you find interesting) `…/pythia8135/htmldoc/Welcome.html`

Back in the `examples/` directory, open the README file to look for more interesting example programs

PDG Codes

A. Fundamental objects

1	d	11	e^-	21	g					add $-$ sign for antiparticle, where appropriate
2	u	12	ν_e	22	γ	32	Z'^0			
3	s	13	μ^-	23	Z^0	33	Z''^0			
4	c	14	ν_μ	24	W^+	34	W'^+			
5	b	15	τ^-	25	h^0	35	H^0	37	H^+	+ diquarks, SUSY,
6	t	16	ν_τ			36	A^0	39	Graviton	technicolor, . . .

B. Mesons

$100\,|q_1| + 10\,|q_2| + (2s+1)$ with $|q_1| \geq |q_2|$

particle if heaviest quark u, $\bar{s}$, c, $\bar{b}$; else antiparticle

111	π^0	311	K^0	130	K^0_L	221	η^0	411	D^+	431	D^+_s
211	π^+	321	K^+	310	K^0_S	331	η'^0	421	D^0	443	J/ψ

C. Baryons

$1000\,q_1 + 100\,q_2 + 10\,q_3 + (2s+1)$

with $q_1 \geq q_2 \geq q_3$, or Λ-like $q_1 \geq q_3 \geq q_2$

2112	n	3122	Λ^0	2224	Δ^{++}	3214	Σ^{*0}
2212	p	3212	Σ^0	1114	Δ^-	3334	Ω^-