School and Workshop "Recent Advances in Fundamental Physics"
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# Comparison of identified hadron yields and event shape variables extracted from Pythia6 & Pythia8 Monte Carlo event generators

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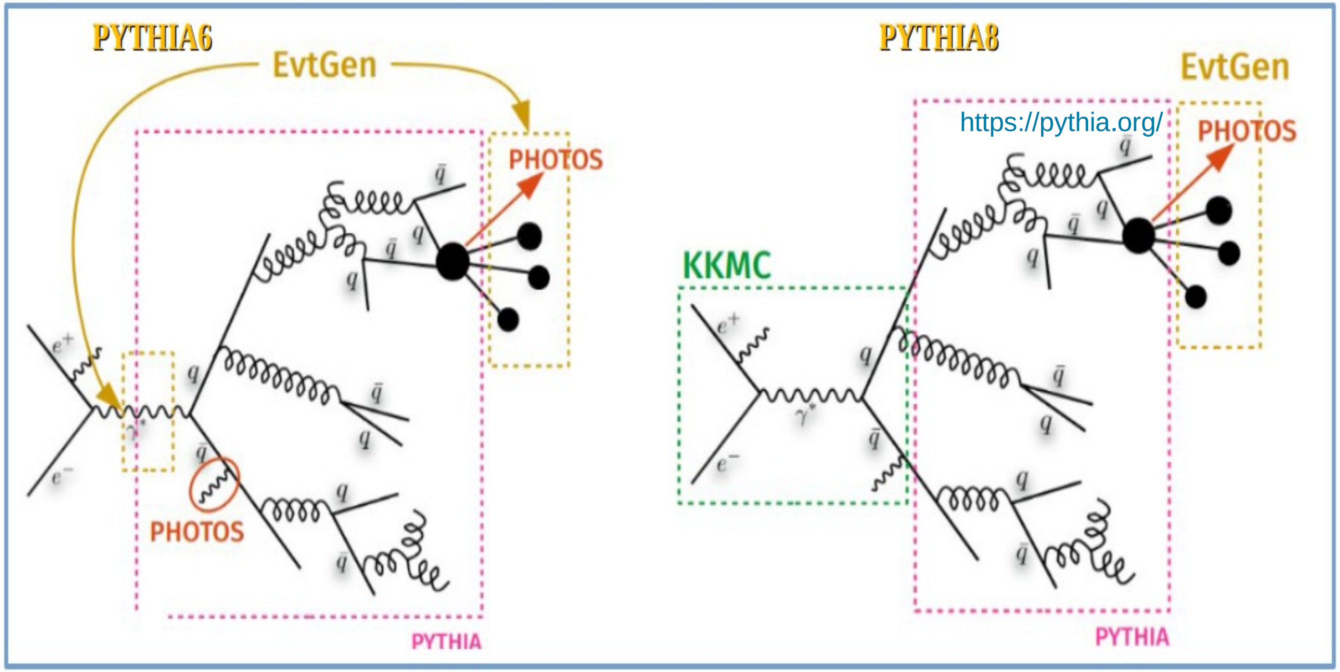
REGIONAL DOCTORAL PROGRAM IN THEORETICAL AND EXPERIMENTAL PARTICLE PHYSICS

# Pythia6 → Pythia8: Monte Carlo generators




**PYTHIA** is a program for the generation of **high-energy physics** collision events, i.e. for the description of collisions at high energies between electrons, protons, photons and heavy nuclei. **It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and decay.** It is largely based on original research, but also borrows many formulae and other knowledge from the literature. As such it is categorized as a general purpose Monte Carlo event generator.

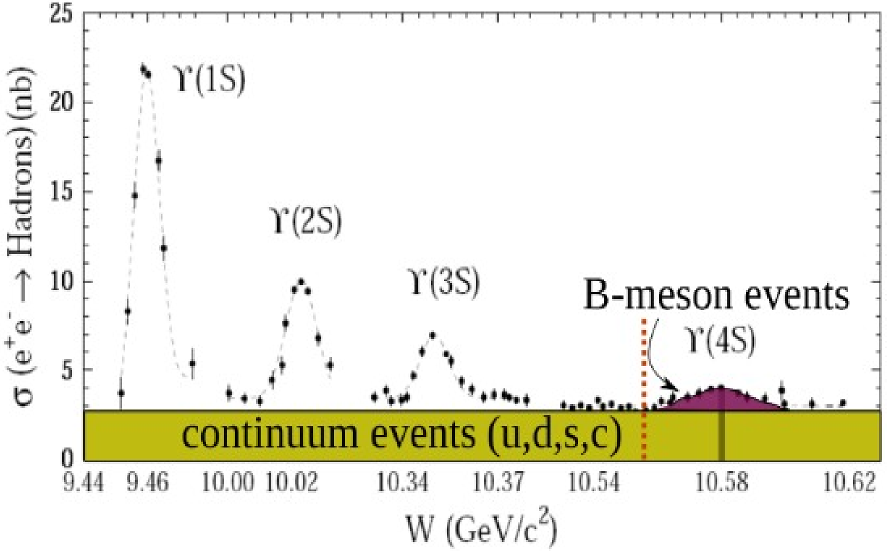


https://pythia.org/

# The continuum events

Along with **B mesons at the same center of mass energies quark-antiquark qqbar (q=u,d,s,c) pairs are produced which are referred to as “continuum background”. For some channels of B decays the continuum events are often considered to be the dominant source of background.** It is also one of the main contributors in systematic uncertainties in precision measurements of **b** → **c** decays. **Therefore the suppression of continuum background is one of the main challenges in B-factories requiring a good description of continuum events between the experimental data and Monte Carlo simulations.**

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

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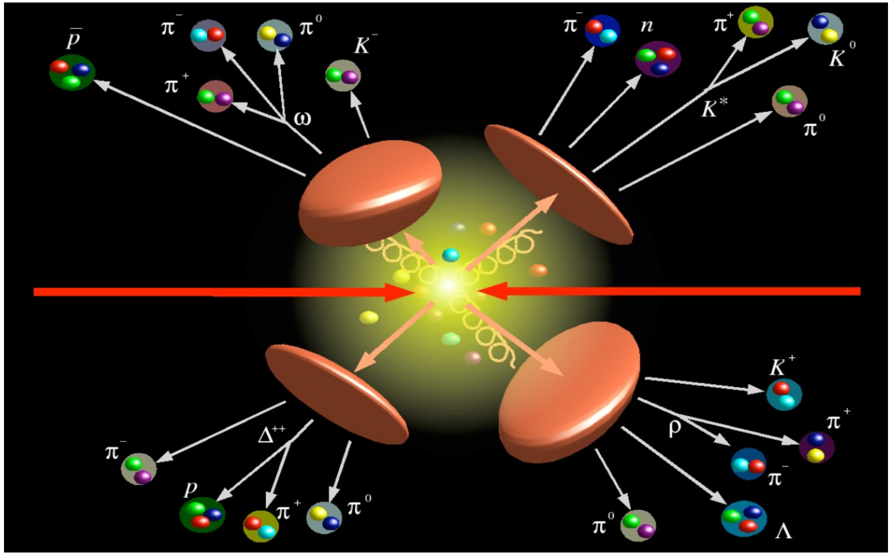
# Pythia6 / Pythia8

Continuum event simulation is done by using **Pythia 8.215** and **Pythia 6.202** . All kinematic variables have been computed in the Center of Momentum (CM) frame. We have generated samples of uubar, ddbar, ssbar, ccbar which then materialized into hadrons by using Pythia event generators. The final state hadrons i.e. **$\pi^+$, $\pi^-$, $K^+$, $K^-$, proton, anti-proton and gammas** are selected with the following cuts:

**p > 0.3 [GeV/c]**

**$p_T$ > 0.1 [GeV/c]**

**True particle ID**




*Schematic view of hadronization/fragmentation process.*

# Event Shape variables

Important feature of physics event is the characterization of an **"event shape"** reconstructed from measured hadron yields which allows to separate physics events produced in various physics processes. It is well known that an "event shape" can be described by **Fox-Wolfram moments** [1] as it is shown in Eq. 1.

$$H_\ell^x = \sum_{i,j=1}^{N} W_{ij}^x \, P_\ell(\cos \Omega_{ij})$$

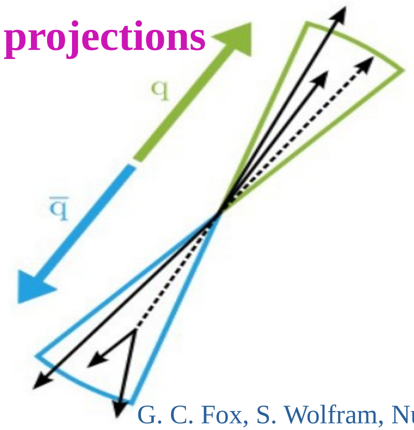
where $W_{ij}^x$ is a weight factor and $P_l(\cos \Omega_{ij})$ is the Legendre polynomial. Commonly used variables for an "event shape" description are variables **Thrust** and **R2 (Fox-Wolfram's second moment)**

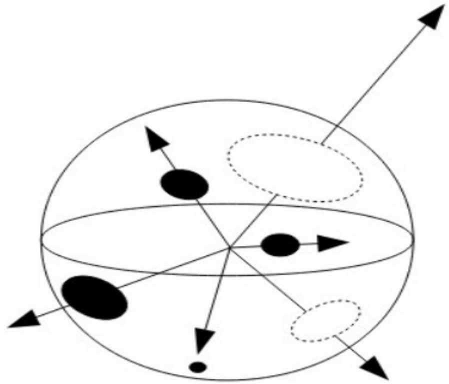
**The thrust axis is the axis that maximizes the longitudinal projections of the particles' momenta**

Thrust

$$T(\vec{v}_T) = \max_{|v_T|=1} \frac{\sum_i |\vec{v}_T \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

Thrust axis



G. C. Fox, S. Wolfram, Nucl. Phys. B149, 413 (1979).

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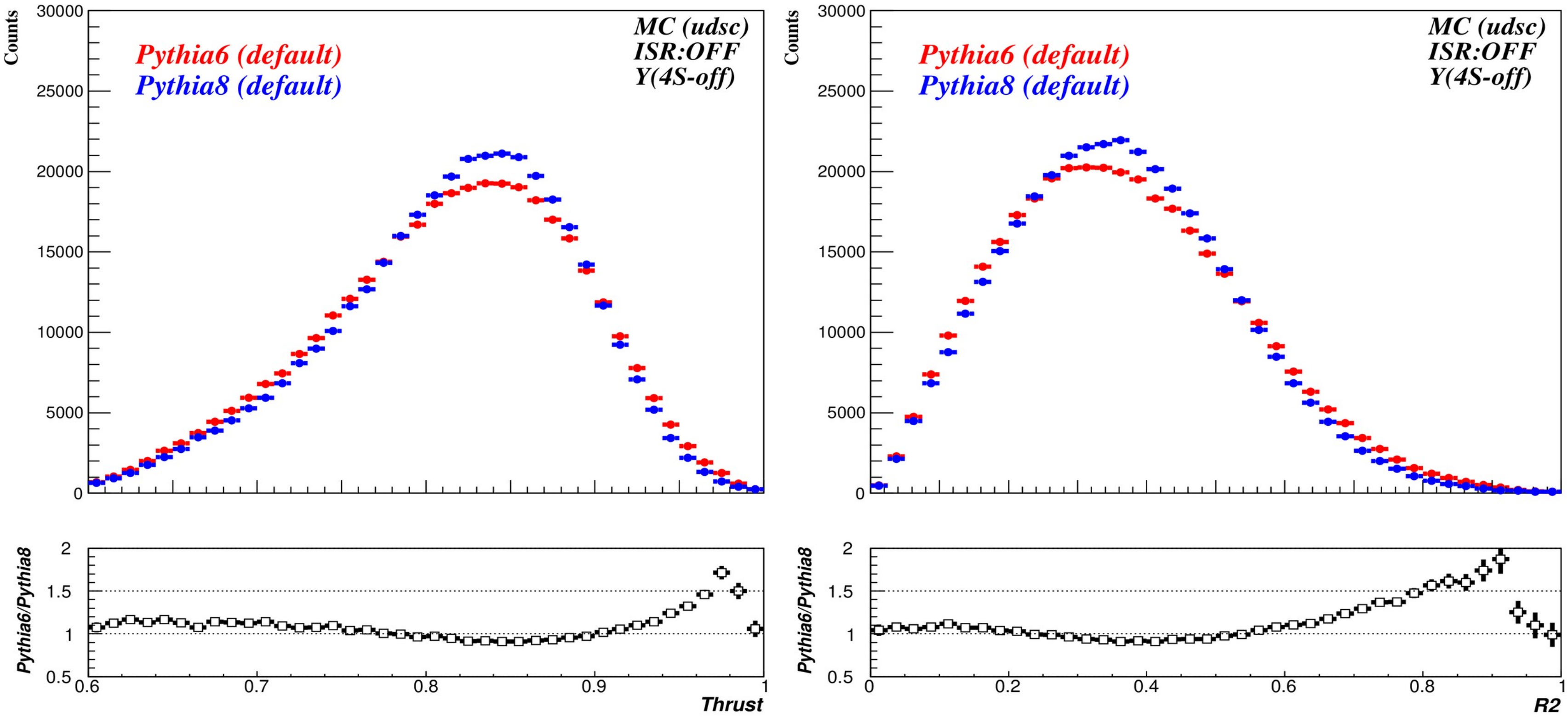
# Pythia6 vs. Pythia8 parameters & values

| **Pythia 8.215** | **Pythia 6.202** | **Pythia 8.215** Default values | **Pythia 6.202** Default values |
|---|---|---|---|
| StringZ:aLund | PARJ(41) | 0.68 | 0.3 |
| StringZ:bLund | PARJ(42) | 0.98 | 0.58 |
| StringPT:sigma | PARJ(21) | 0.335 | 0.36 |
| StringFragmentation:stopMass | PARJ(33) | 1 | 0.8 |
| StringFlav:etaSup | PARJ(25) | 0.6 | 1 |
| StringFlav:etaPrimeSup | PARJ(26) | 0.12 | 0.4 |
| TimeShower:pTmin | PARJ(82) | 0.5 | 1 |
| StringZ:aExtraDiquark | PARJ(45) | 0.97 | 0.5 |
| StringZ:rFactC | PARJ(46) | 1.32 | 1 |
| StringPT:enhancedFraction | PARJ(23) | 0.01 | 0.01 |
| StringPT:enhancedWidth | PARJ(24) | 2 | 2 |
| StringFragmentation:stopSmear | PARJ(37) | 0.2 | 0.2 |
| MiniStringFragmentation:nTry | MSTJ(17) | 2 | 2 |
| HadronLevel:mStringMin | MSTJ(14) | 1 | 1 |
| StringFragmentation:eBothLeftJunction | PARJ(49) | 1 | 1 |
| StringFlav:probStoUD | PARJ(2) | 0.217 | 0.3 |
| StringFlav:probQQtoQ | PARJ(1) | 0.081 | 0.1 |
| StringFlav:probSQtoQQ | PARJ(3) | 0.915 | 0.4 |
| StringFlav:probQQ1toQQ0 | PARJ(4) | 0.0275 | 0.05 |
| StringFlav:mesonUDvector | PARJ(11) | 0.5 | 0.5 |
| StringFlav:mesonSvector | PARJ(12) | 0.55 | 0.6 |

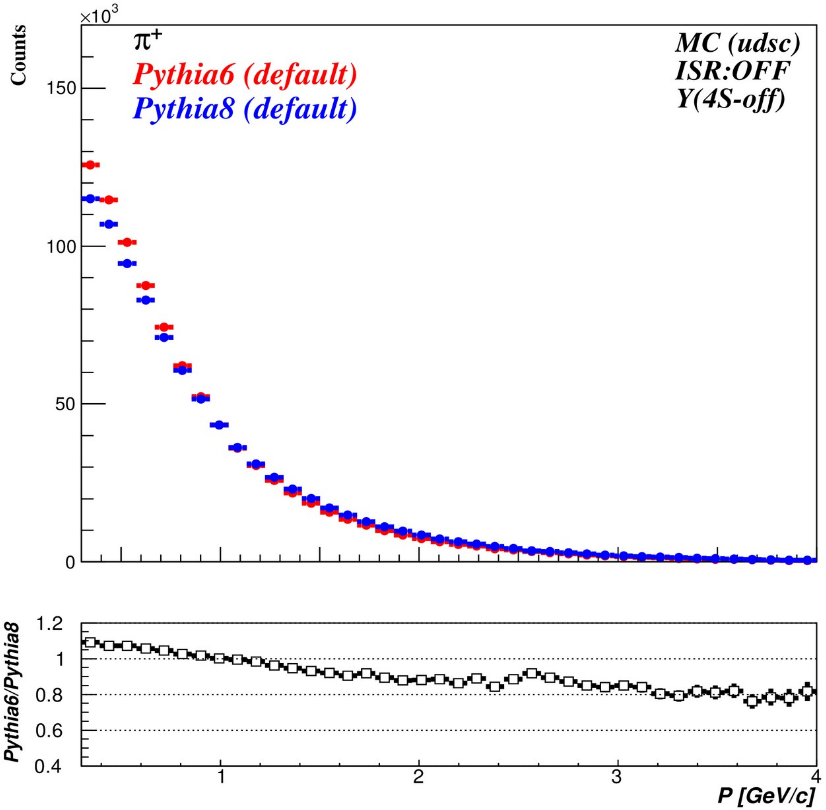
| **Pythia 8.215** | **Pythia 6.202** | **Pythia 8.215** Default values | **Pythia 6.202** Default values |
|---|---|---|---|
| StringFlav:mesonCvector | PARJ(13) | 0.88 | 0.75 |
| StringFlav:mesonUDL1S0J1 | PARJ(14) | 0 | 0 |
| StringFlav:mesonUDL1S1J0 | PARJ(15) | 0 | 0 |
| StringFlav:mesonUDL1S1J1 | PARJ(16) | 0 | 0 |
| StringFlav:mesonUDL1S1J2 | PARJ(17) | 0 | 0 |
| StringFlav:decupletSup | PARJ(18) | 1 | 1 |
| StringFlav:popcornSpair | PARJ(6) | 0.9 | 0.5 |
| StringFlav:popcornSmeson | PARJ(7) | 0.5 | 0.5 |
| TimeShower:pTminChgQ | PARJ(83) | 0.5 | 1 |
| MultipartonInteractions:expPow | PARP(83) | 1.85 | 1 |
| MultipartonInteractions:pT0Ref | PARP(82) | 2.28 | 1.9 |
| MultipartonInteractions:ecmPow | PARP(90) | 0.215 | 0.16 |
| MultipartonInteractions:coreRadius | PARP(84) | 0.4 | 0.2 |

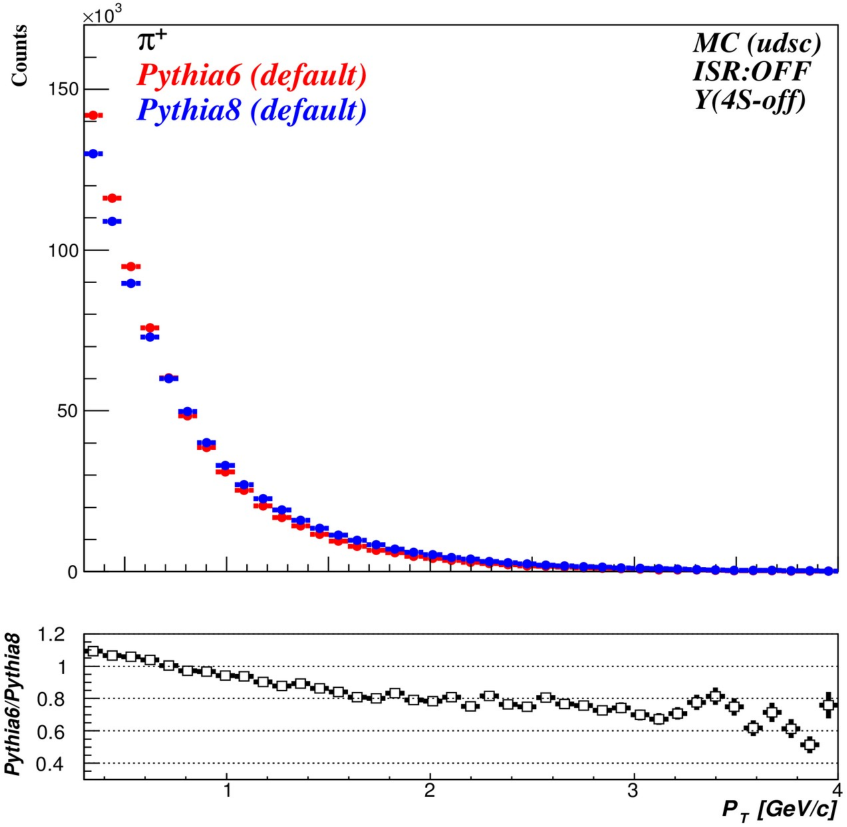
one-to-one correspondence between Pythia6 & Pythia8 parameters and their default values

# Pythia6 vs. Pythia8 comparison on the generator level



# Pythia6 vs. Pythia8 comparison on the generator level

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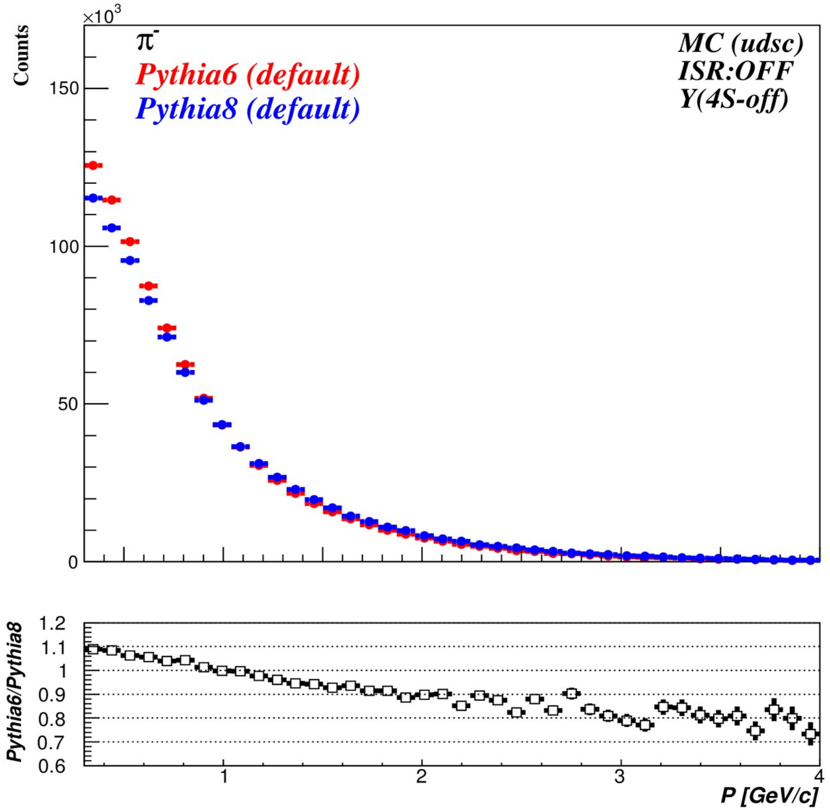
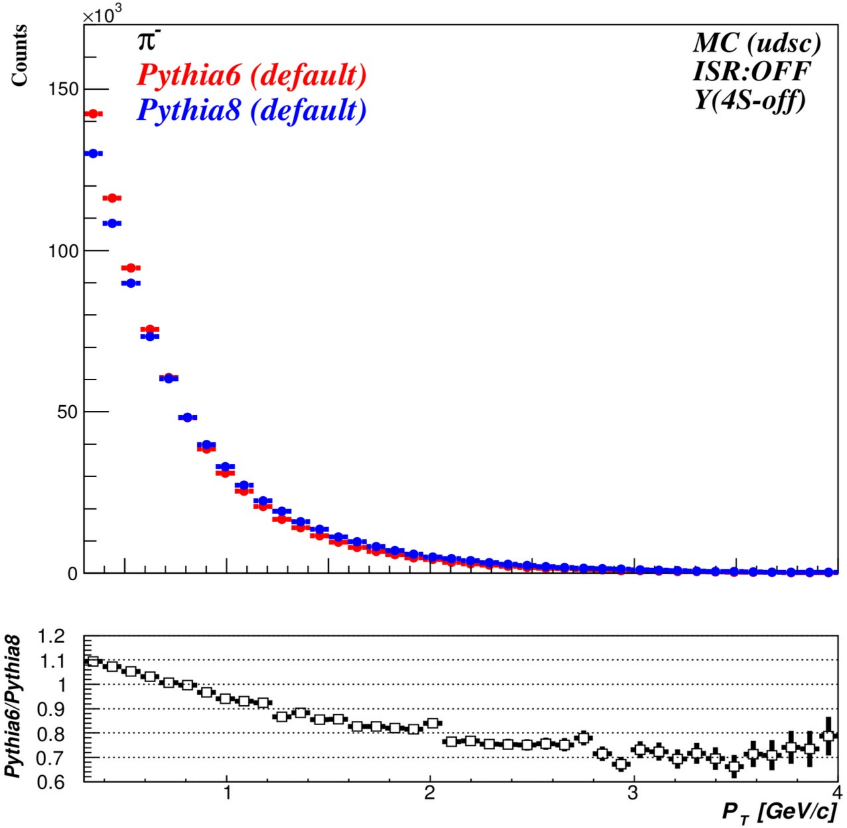
# Pythia6 vs.  Pythia8 comparison on the generator level

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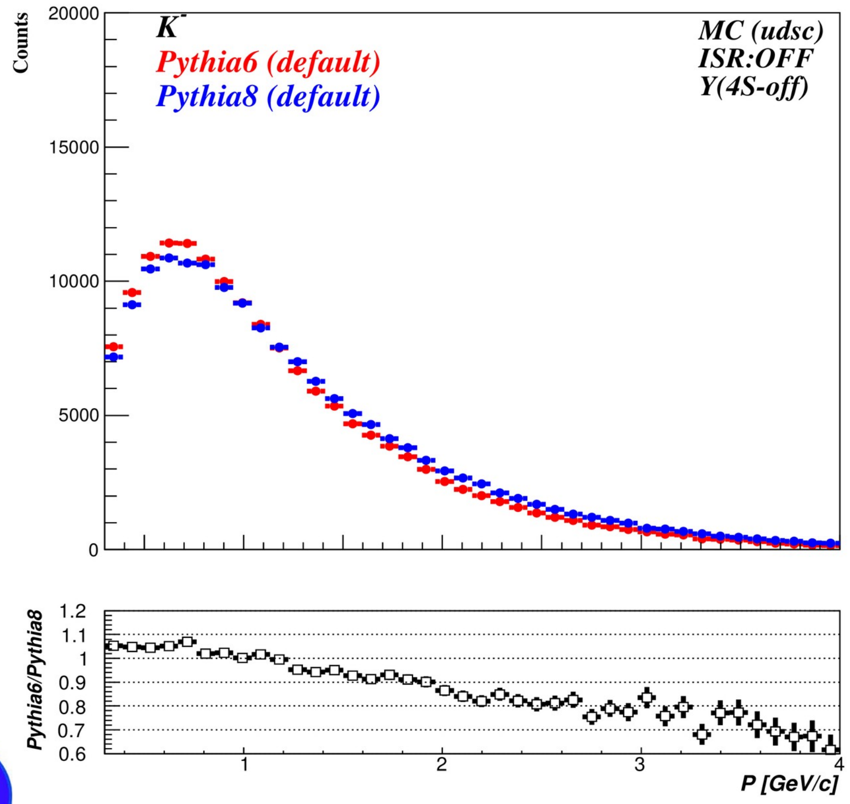
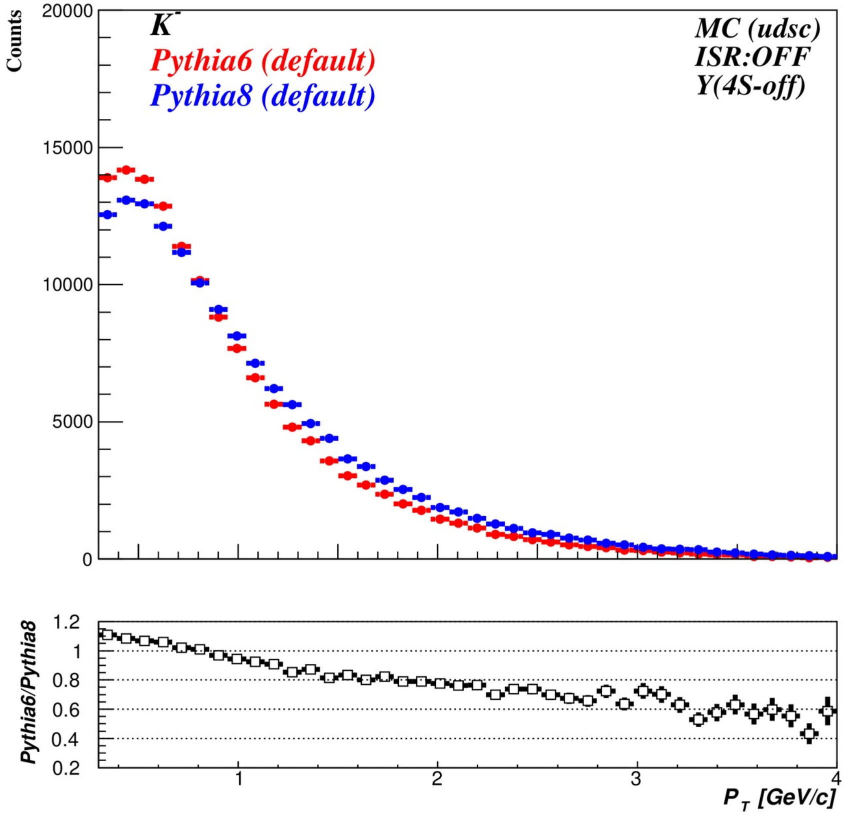
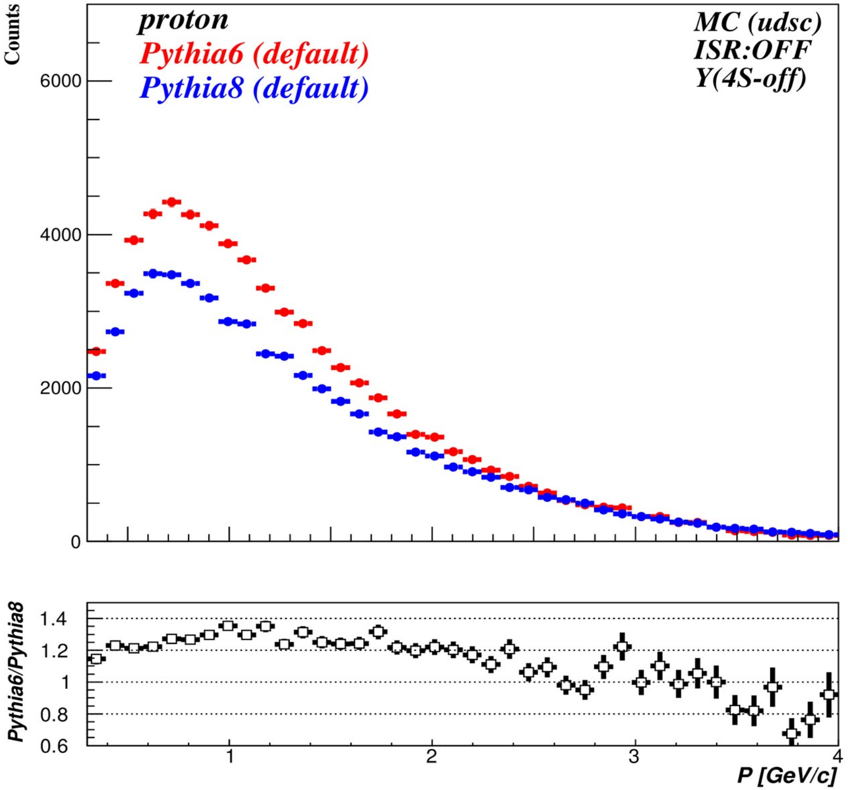
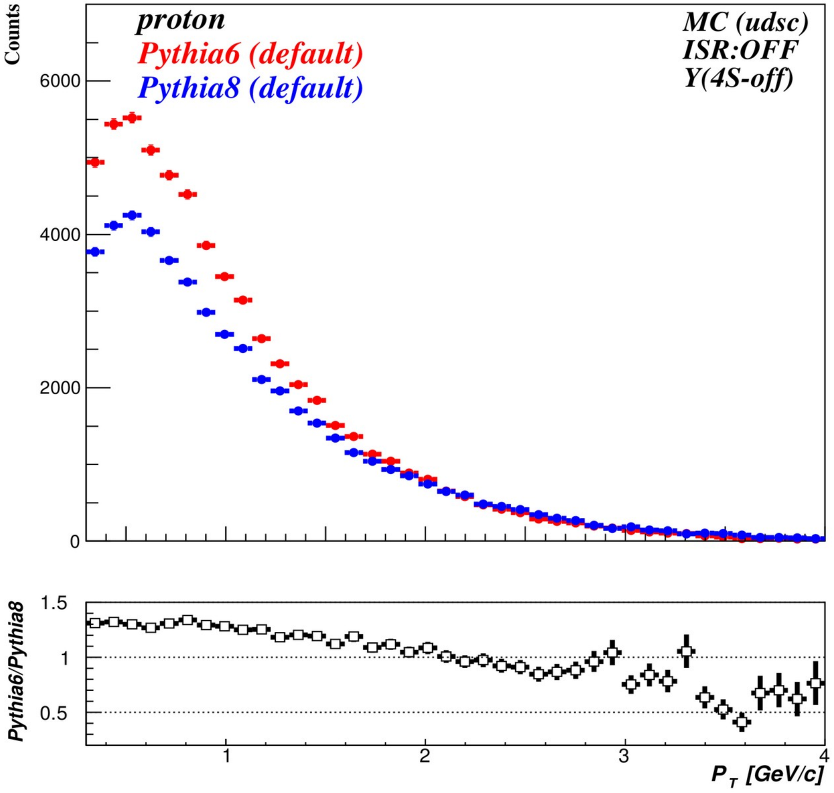
# Pythia6 vs. Pythia8 comparison on the generator level



# Pythia6 vs.  Pythia8 comparison on the generator level

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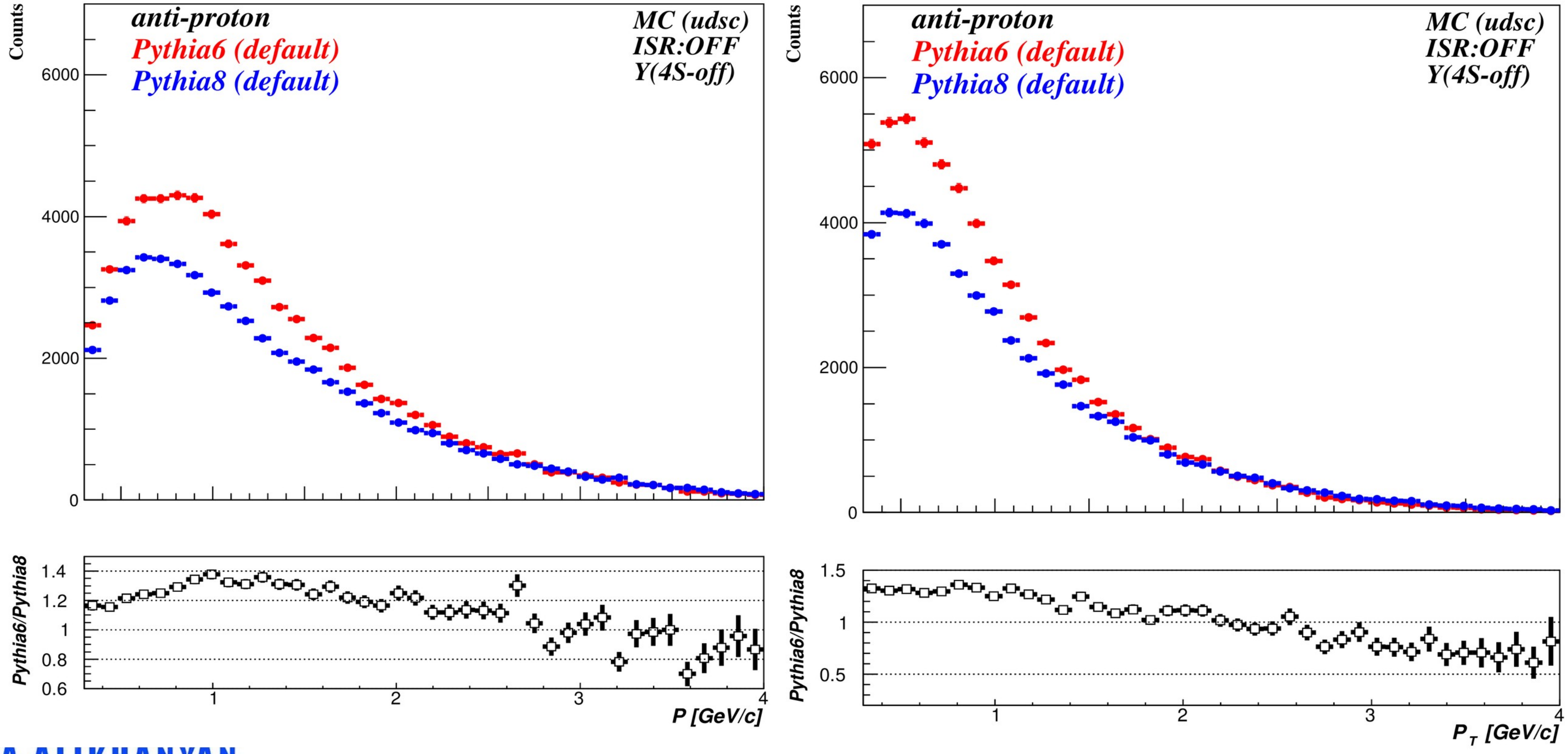
# Pythia6 vs. Pythia8 comparison on the generator level



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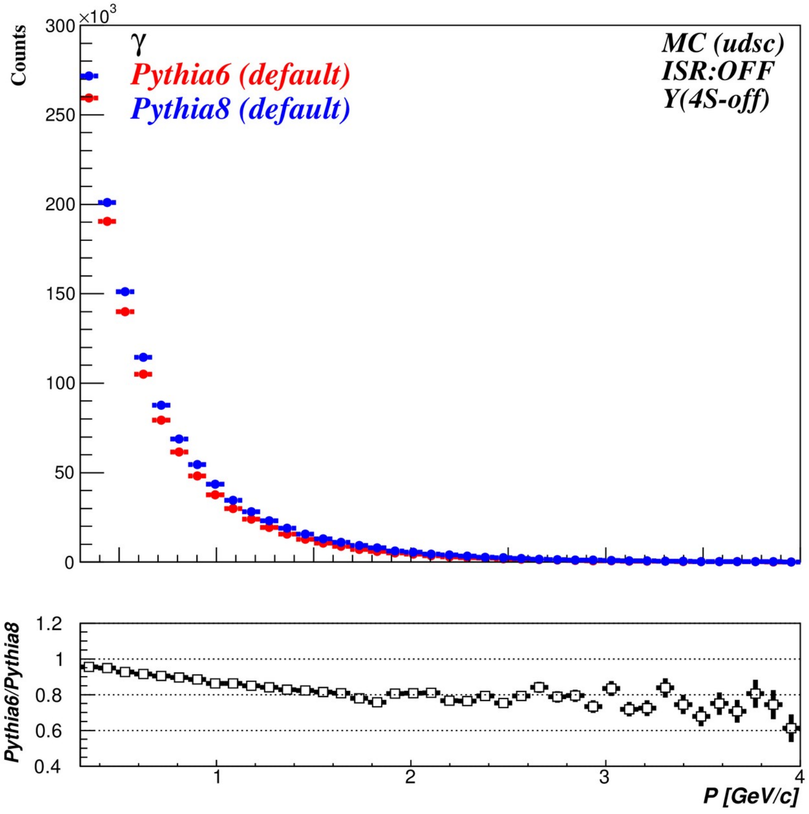
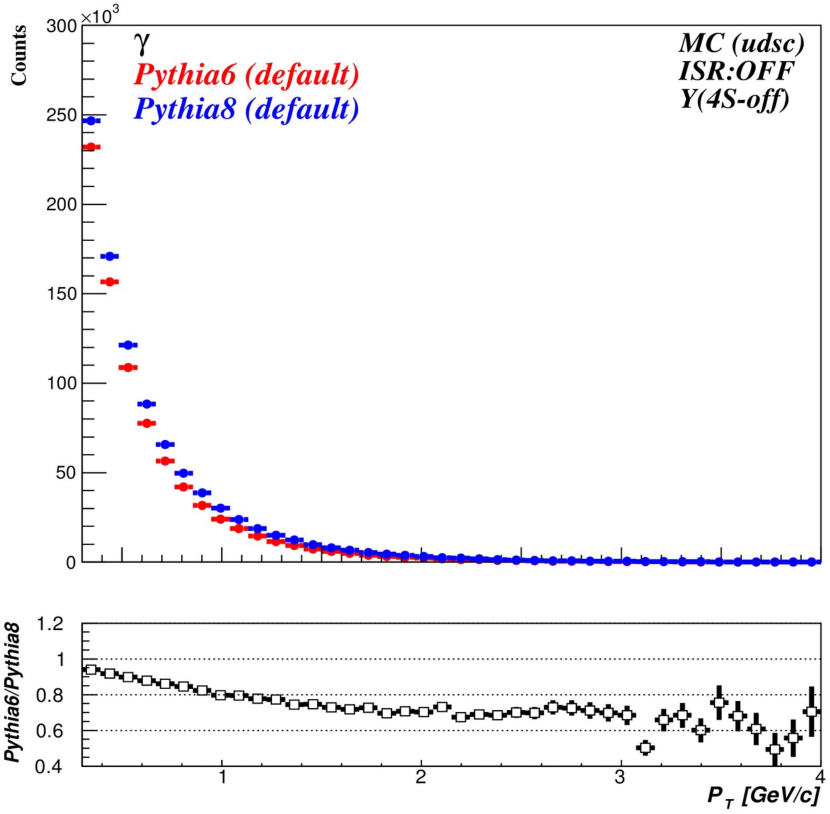
# Pythia6 vs. Pythia8 comparison on the generator level

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# Table of correspondence (ToC)

- StringFlav:mesonCvector=0.75 → PARJ(13)=0.75
- StringFlav:mesonUDL1S0J1=0 → PARJ(14)=0
- StringFlav:mesonUDL1S1J0=0 → PARJ(15)=0
- StringFlav:mesonUDL1S1J1=0 → PARJ(16)=0
- StringFlav:mesonUDL1S1J2=0 → PARJ(17)=0
- StringFlav:decupletSup=1 → PARJ(18)=1
- StringFlav:popcornSpair=0.5 → PARJ(6)=0.5
- StringFlav:popcornSmeson=0.5 → PARJ(7)=0.5
- TimeShower:pTminChgQ=1 → PARJ(83)=1
- MultipartonInteractions:expPow=1 → PARP(83)=1
- MultipartonInteractions:pT0Ref=1.9 → PARP(82)=1.9
- MultipartonInteractions:ecmPow=0.16 → PARP(90)=0.16
- MultipartonInteractions:coreRadius=0.2 → PARP(84)=0.2
- StringZ:aLund=0.32 → PARJ(41)=0.32
- StringZ:bLund=0.62 → PARJ(42)=0.62
- StringPT:sigma=0.42 → PARJ(21)=0.42
- StringFragmentation:stopMass=0.3 → PARJ(33)=0.3
- StringFlav:etaSup=0.27 → PARJ(25)=0.27
- StringFlav:etaPrimeSup=0 → PARJ(26)=0
- StringZ:aExtraDiquark=0.5 → PARJ(45)=0.5
- StringZ:rFactC=1 → PARJ(46)=1
- StringPT:enhancedFraction=0.01 → PARJ(23)=0.01
- StringPT:enhancedWidth=2 → PARJ(24)=2
- StringFragmentation:stopSmear=0.2 → PARJ(37)=0.2
- MiniStringFragmentation:nTry=2 → MSTJ(17)=2
- HadronLevel:mStringMin=1 → MSTJ(14)=1
- StringFragmentation:eBothLeftJunction=1 → PARJ(49)=1
- StringFlav:probStoUD=0.3 → PARJ(2)=0.2
- StringFlav:probQQtoQ=0.1 → PARJ(1)=0.1
- StringFlav:probSQtoQQ=0.4 → PARJ(3)=0.4
- StringFlav:probQQ1toQQ0=0.05 → PARJ(4)=0.05
- StringFlav:mesonUDvector=0.5 → PARJ(11)=0.5
- StringFlav:mesonSvector=0.6 → PARJ(12)=0.6
- TimeShower:pTmin=0.5 → PARJ(82)=0.5
- TimeShower:alphaSvalue=0.1365 → PARJ(81)=0.3

**PYTHIA6 PARJ(81)** : (D = 0.29 GeV) Λ value in running αs for parton showers. This is used in all user calls to PYSHOW, in the PYEEVT/PYONIA e+e− routines, and in a resonance decay.

**PYTHIA8 TimeShower:alphaSvalue** : (default = 0.1383; minimum = 0.06; maximum = 0.25) the αs value at scale MZ2.The default value corresponds to a crude tuning to LEP data, to be improved.

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln\left(\frac{Q^2}{\Lambda^2}\right)} \qquad \text{(first order)}$$

where $n_f = 5, Q^2 = M_Z^2, \Lambda = PARJ(81)$

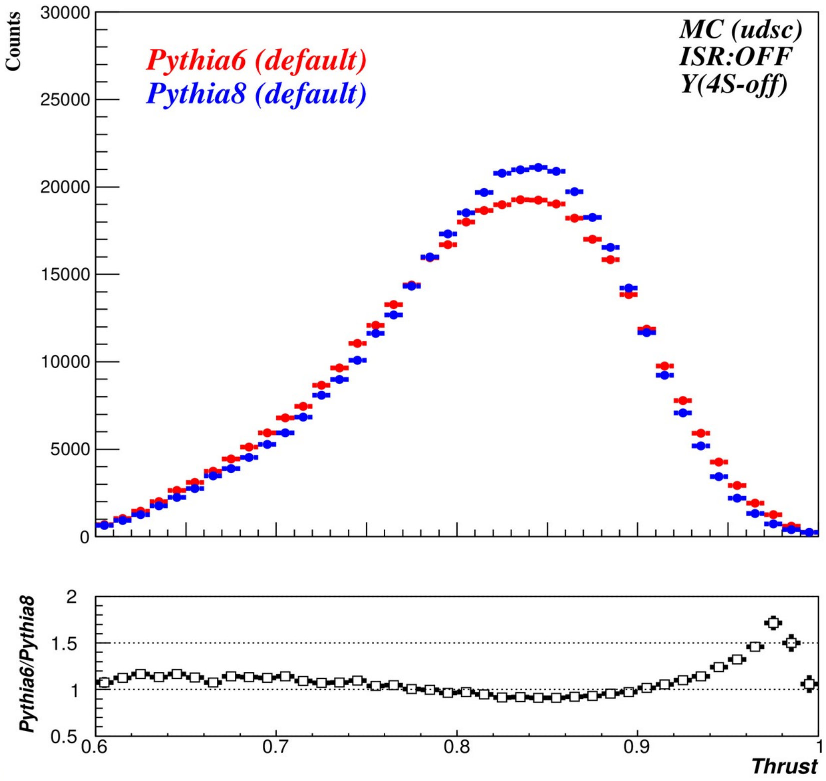
**PYTHIA6 PARJ(82)** : (D = 1.0 GeV) (Q0) invariant mass cut-off $m_{min}$ of PYSHOW parton showers, below which partons are not assumed to radiate.

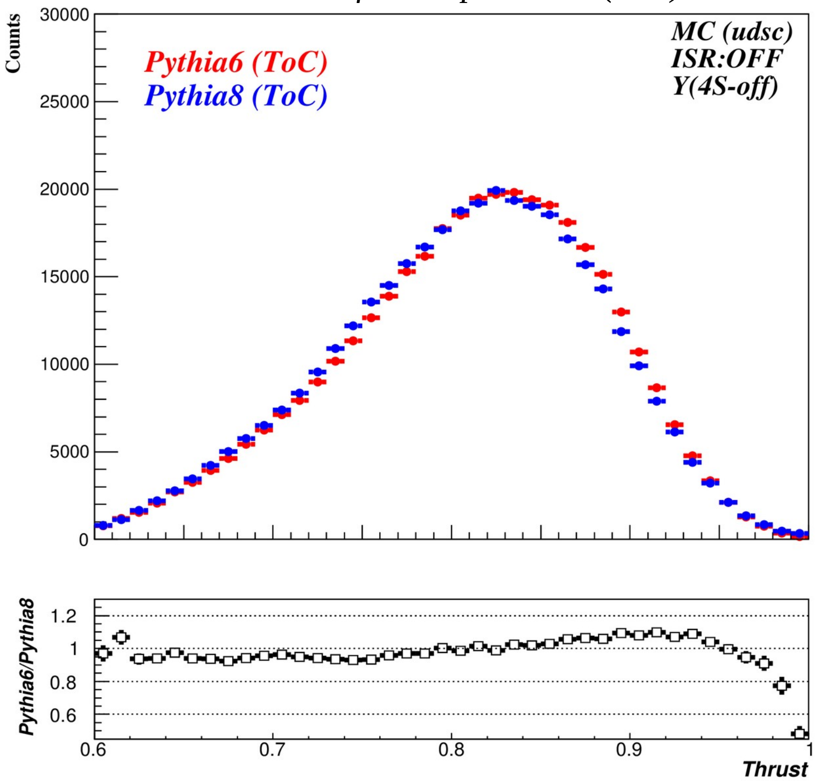
**PYTHIA8 TimeShower:pTmin** : (default = 0.5; minimum = 0.1; maximum = 2.0) parton shower cut-off $p_T$ for QCD emission.

**PTMIN** : lower scale of shower evolution. For QCD evolution, an absolute lower limit is set by **PARJ(82)/2** or 1.1 x $\Lambda_{QCD}^{(3)}$ whichever is larger.

# Pythia6 vs.  Pythia8 comparison on the generator level

*Table of correspondence (ToC)*

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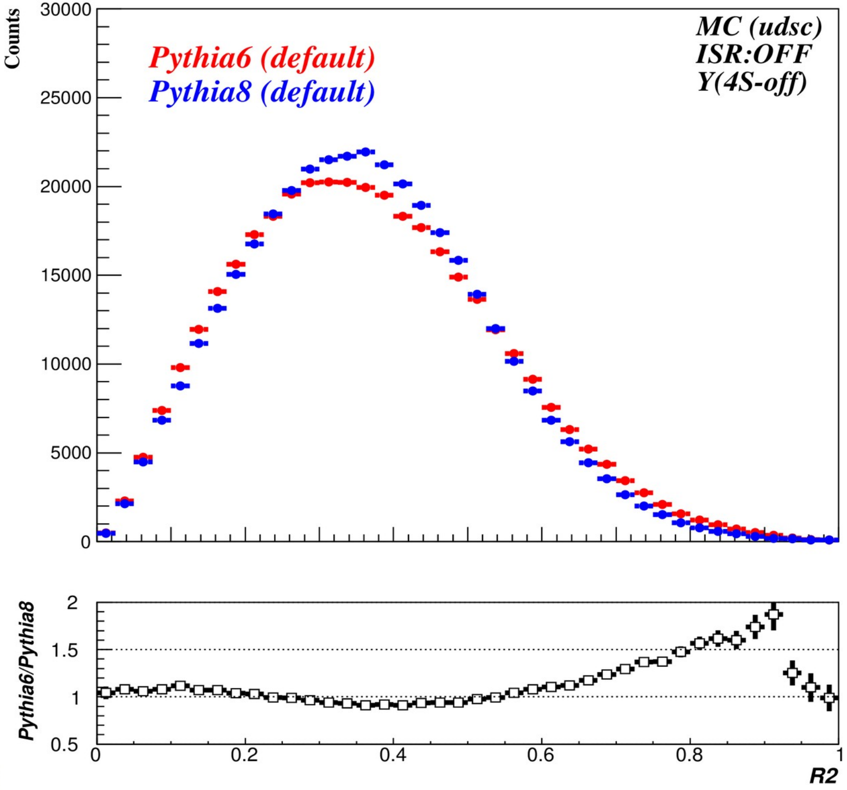
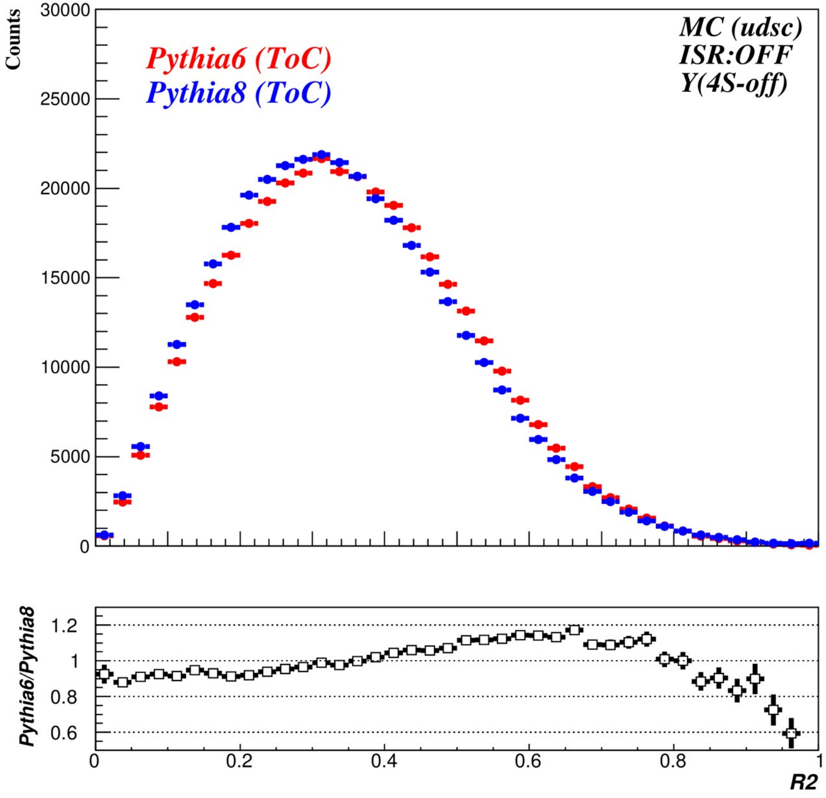
# Pythia6 vs.  Pythia8 comparison on the generator level




<u>*Table of correspondence (ToC)*</u>

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# Parameter sensitivity check

**PYTHIA8 more than 100 parameters → can't tune all at once**

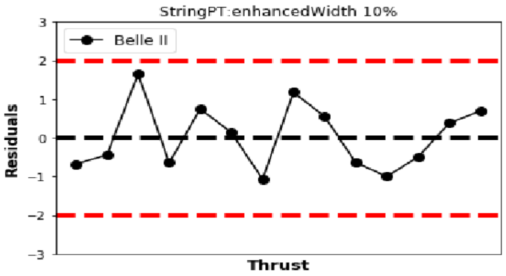
**Normalized Residuals**

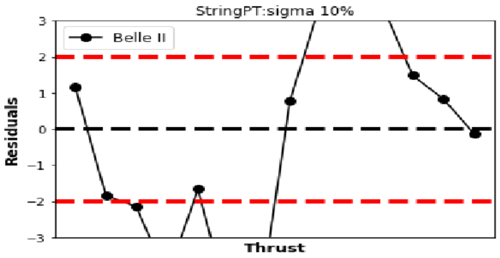
$$r_i = \frac{n_i - N\hat{p}_i}{\sqrt{N\hat{p}_i}\sqrt{(1-N/(N+M))(1-(n_i+m_i)/(N+M))}}$$

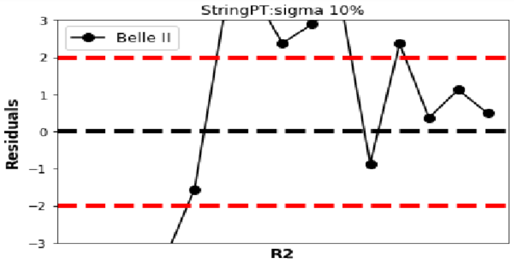
$$\hat{p}_i = \frac{n_i + m_i}{N + M}$$

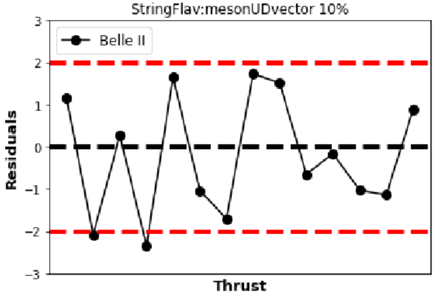
**$n_i$** → number of events in $i^{th}$ bin in the default sample
**N** → total number of events in the default sample
**$m_i$** → number of events in $i^{th}$ bin in the modified sample
**M** → total number of events in the modified sample

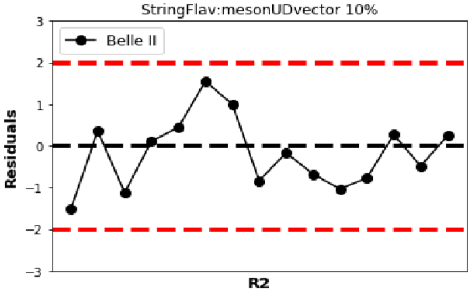
- two sample test between default sample and sample with the modified parameter values.

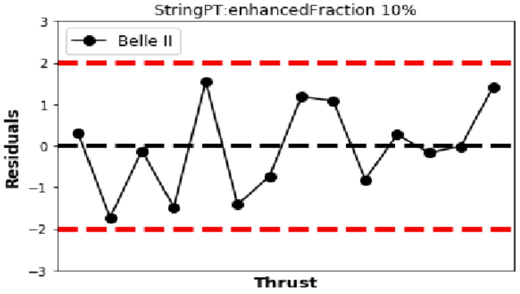


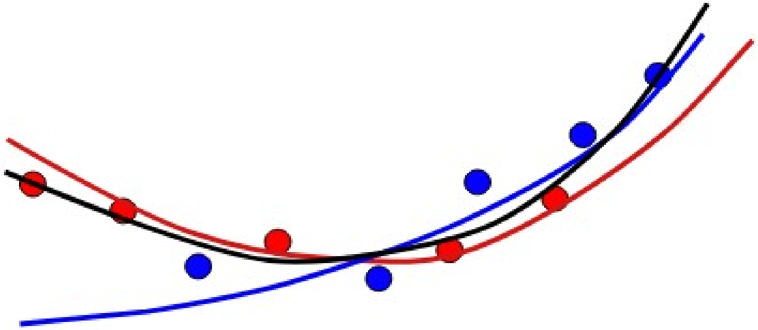



# Tuning tool: Professor2



- a tuning tool for Monte Carlo event generators
- automated tuning approach
- tune itself is very fast
- professor supplies the parameter grid
- generate Monte Carlo for a given set of parameter values
- calculate observables
- build interpolations  (parametrise the MC in parameter space with a polynomial)
- parametrise the MC in parameter space with a polynomial
- tune polynomial to data (determination of minimum in parameters space)

# Tuning tool: Professor2

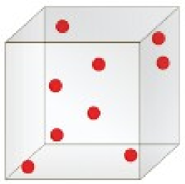
To account for lowest-order parameter correlations, a polynomial of at least second-order is used as the basis for bin parameterisation:

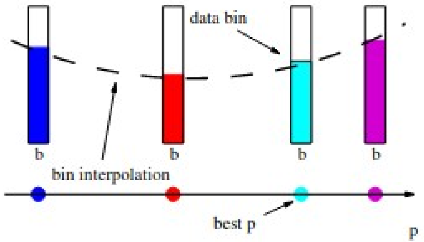
$$\mathrm{MC}_b(\boldsymbol{p}) \approx f^{(b)}(\boldsymbol{p}) = \alpha_0^{(b)} + \sum_i \beta_i^{(b)} p'_i + \sum_{i \le j} \gamma_{ij}^{(b)} p'_i p'_j$$

where the shifted parameter vector $\boldsymbol{p}' \equiv \boldsymbol{p} - \boldsymbol{p}_0$

1. Random sampling: $N$ parameter points in $n$-dimensional space
2. Run generator and fill histograms
3. For each bin: use $N$ points to fit interpolation ($2^{nd}$ or $3^{rd}$ order polynomial)
4. Construct overall (now trivial) $\chi^2 \approx \sum_{bins} \frac{(interpolation - data)^2}{error^2}$
5. and Numerically *minimize* `pyMinuit, SciPy`

| Num params, $P$ | $N_2^{(P)}$ (2nd order) | $N_3^{(P)}$ (3rd order) |
|---|---|---|
| 1 | 3 | 4 |
| 2 | 6 | 10 |
| 4 | 15 | 35 |
| 6 | 28 | 84 |
| 8 | 45 | 165 |
| 10 | 66 | 286 |

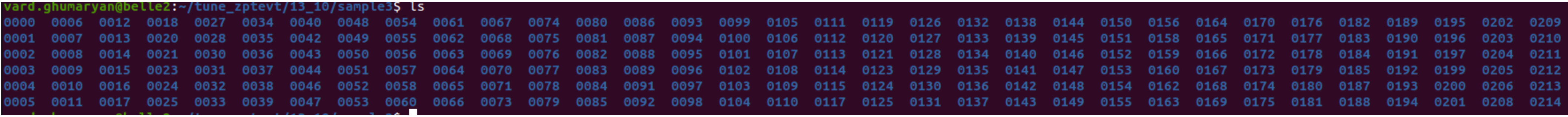




# Tuning tool: Professor2

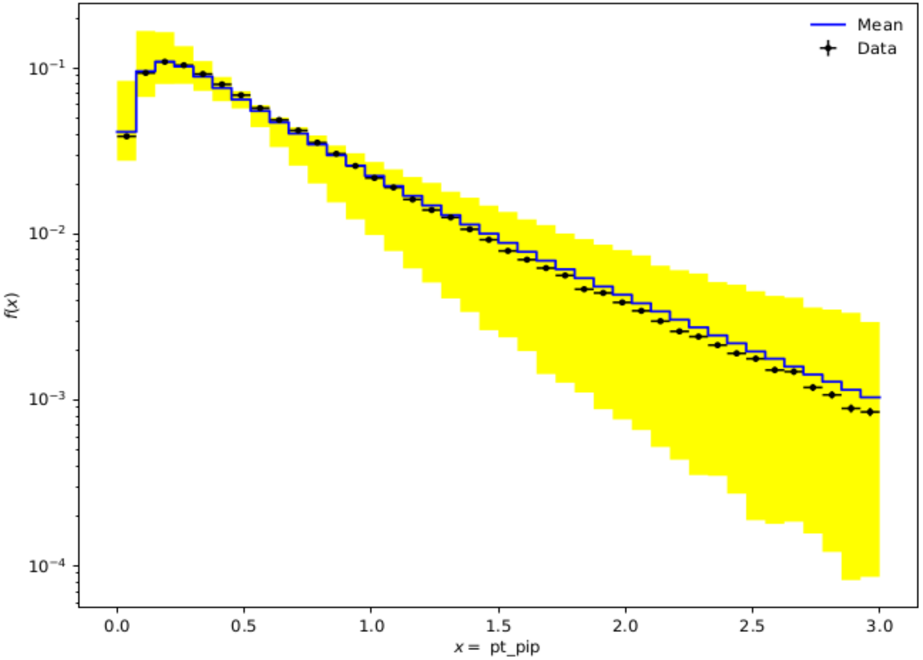
The **“Professor2”** is an open source package easy to implement in common Unix environment.


At the first step of the tuning process, one should define a set of parameters and the spectra of various observables have to be generated. For this, the “Professor2” package has a function that allows to generate a random values of parameters in a given range: Having the set of parameters extracted one can start to generate the MC samples by using different parameter sets. The generated pseudo-data are saved in ROOT files for each specific process.



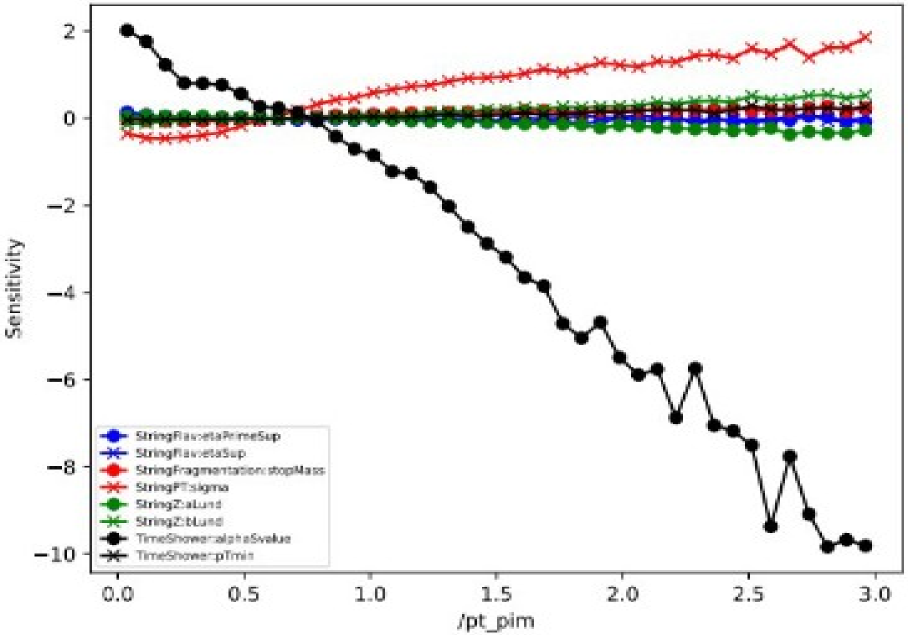

After which interpolate histo bin values as a function of the parameter space by loading run data and parameter lists from run directories. As a result, we get the ipol.dat file needed for the tuning. The main tuning stage performs the optimisation of MC samples against reference data for each distribution extracted from MC run combinations with different parameter sets.

# Tuning tool: Professor2




**Prof2-envelopes** command line makes histograms showing the range of variation available on the histograms of kinematic observables obtained from the various MC samples.

**prof2-I** - is a graphical user interface which reads reference data and ipol.dat files and interactively shows us how variations of parameters will affect on a particular obsevable. One can also find a sensitivity of a particular kinematic distribution versus parameter used to generate the pseudo-data. It can be done by using prof2-sens ipol.dat



The main tuning stage should be done via the **prof2-tune** program. It performs the optimisation of MC samples against reference data for each distribution extracted from MC run combinations with different parameter sets. The run combinations can either be uniquely and randomly generated at run-time by **prof2-tune**, or can be supplied via a plain text file in which each line is a white-space separated list of run names.

parameter values before tuning.

StringFlav:etaSup = 0.27
StringFlav:etaPrimeSup = 0.12
StringZ:aLund = 0.32
StringZ:bLund = 0.62
StringPT:sigma = 0.42
StringPT:enhancedFraction = 0.01
StringFlav:probStoUD = 0.3
StringFlav:probQQtoQ = 0.1
StringZ:rFactC = 1

```
# ProfVersion: 2.3.3
# Date: 2022-01-27 22:17:12
# InterpolationFile: /home/vard.ghumaryan/grid_tune_uds/tune_21/ipol.dat
# DataDirectory: /home/vard.ghumaryan/grid_tune_uds/tune_21/REF_HIST_21
#
# Limits:
#       StringFlav:etaSup                0.101794 0.899365
#       StringFlav:etaPrimeSup           0.057382 0.799047
#       StringZ:aLund                    0.100069 1.498153
#       StringZ:bLund                    0.301898 1.592890
#       StringPT:sigma                   0.053686 0.899973
#       StringPT:enhancedFraction        0.001378 0.799354
#       StringFlav:probStoUD             0.052006 0.799968
#       StringFlav:probQQtoQ             0.016077 0.798140
#       StringZ:rFactC                   0.101781 1.799188
#
# Fixed:
#
# Minimisation result:
#
# GOF 2222.832707
# UNITGOF 2222.832707
# NDOF 471.000000
StringFlav:etaSup               0.269576
StringFlav:etaPrimeSup          0.119462
StringZ:aLund                   0.179521
StringZ:bLund                   0.488778
StringPT:sigma                  0.191794
StringPT:enhancedFraction       0.729152
StringFlav:probStoUD            0.208804
StringFlav:probQQtoQ            0.080138
StringZ:rFactC                  0.773285
#
```

# conclusion

- 1) Pythia6 vs. Pythia8 comparison is done for event shape variables Thrust, $R_2$ and momentum spectra for identified hadrons

- 2) One-to-one correspondence table is made for Pythia6 and Pythia8 parameters

- 3) Tuning procedure for Pythia8 Monte Carlo with Professor2 tool