MCSTHAR++, implementation of the Statistical Hadronization Model in HERWIG - Preliminary results

Christopher Bignamini
Università degli Studi di Pavia
INFN Sezione di Pavia
christopher.bignamini@pv.infn.it

In collaboration with
F. Becattini and **F. Piccinini**

Modeling of the Parton-Hadron Phase Transition
Villasimius
23-24 September 2010

Outline

Outline

1. Hadronization models and Event Generators
2. Microcanonical hadronization
3. MCSTHAR++: code description
4. MCSTHAR++: preliminary results
5. Conclusions

Outline

1. Hadronization models and Event Generators
2. Microcanonical hadronization
3. MCSTHAR++: code description
4. MCSTHAR++: preliminary results
5. Conclusions

Outline

1. Hadronization models and Event Generators
2. Microcanonical hadronization
3. MCSTHAR++: code description
4. MCSTHAR++: preliminary results
5. Conclusions

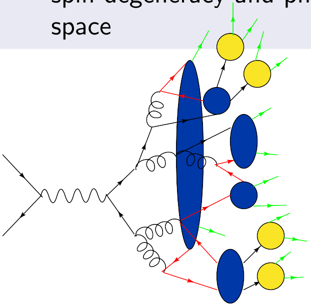
Outline

1. Hadronization models and Event Generators
2. Microcanonical hadronization
3. MCSTHAR++: code description
4. MCSTHAR++: preliminary results
5. Conclusions

Hadronization models (I)

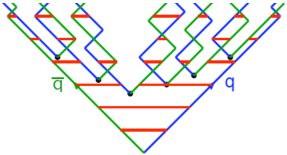
Cluster model

- Implemented in HERWIG and SHERPA
- Final state quarks and antiquarks are coupled to build colorless ”clusters”
- The clusters decay (mostly) into two hadrons according to spin degeneracy and phase space



String model

- Implemented in PYTHIA
- A color string is supposed to connect final state quarks, antiquarks and gluons (linear potential)
- Hadrons come from $q\bar{q}$ produced from the vacuum via string fragmentation



Hadronization models (II)

WHAT ABOUT THE STATISTICAL MODEL???

MCSTHAR++

Monte Carlo STatistical HAdronization in high energy Reactions

In collaboration with

- F. Becattini
- F. Piccinini
- MCnet: Stefan Gieseke, Karlsruhe University (Implementation of MCSTHAR++ in Herwig++)

References:

- Cluster model: HERWIG G. Corcella et al., JHEP 0101 (2001) 010
- String model: PYTHIA T. Sjöstrand et al., JHEP 05 (2006) 026
- Modified cluster model: SHERPA J.C. Winter et al., Eur. Phys. J. C35 (2004) 381

The statistical hadronization model

Basic ideas

- In a high-energy collision there is the production of pre-hadronic extended object called clusters or fireballs
- Each of them has well defined physical quantities

$$P, Q, S, B, C, ...$$

is colour neutral and hadronizes according to a pure statistical law

Microcanonical description

Every localized multi-hadronic state within the cluster compatible with the conservation laws is equally likely

Probability to observe the final state $| f \rangle$

$$p_f \propto \langle f \mid P_i P_V P_i \mid f \rangle \qquad P_i = P_P P_{Q,S,B} \qquad P_V = \sum_{h_V} \mid h_V \rangle \langle h_V \mid$$

Model features and free parameters

Main features

- Bose-Einstein and Fermi-Dirac correlations
- Interactions among the hadrons

Strange particles suppression

$$\langle f \mid P_i P_V P_i \mid f \rangle \Rightarrow {\gamma_s}^{N_s} \langle f \mid P_i P_V P_i \mid f \rangle$$

Free parameters of the model

1. γ_s Strangeness suppression parameter
2. ρ Energy density of the clusters

PYTHIA: 15 parameters
HERWIG: 7 parameters
SHERPA: 15 parameters

References:

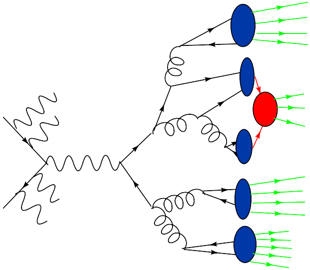
- R. Hagedorn, Nuovo Cim. Suppl. **3** (1965) 147
- F. Becattini, Z. Phys. C **69** (1996) 485
- F. Becattini, U. W. Heinz, Z. Phys. C **76** (1997) 269.
- J. Bernstein, R. Dashen, S. Ma, Phys. Rev. **187** (1969) 1

MCSTHAR++: code description (I)

MCSTHAR++

Monte Carlo STatistical HAdron Reaction

- MCSTHAR++ implements the statistical model in the microcanonical formulation
- It is an Object Oriented C++ code (with a little bit of ROOT) performing the hadronization step taking as input a set of (HERWIG's) clusters and giving in output the primary hadrons
- If needed a reclusterization is performed



- HERWIG's showers and hard scattering
- HERWIG's clustering
- MCSTHAR++'s reclustering
- MCSTHAR++'s hadronization

- The final decay of the unstable hadrons is performed by HERWIG itself

MCSTHAR++: code description (II)

We need to normalize the weight associated to the decay of each cluster

⇓

Knowledge of the partition function is mandatory

Microcanonical Partition Function

$$\Omega\left(M,\gamma_s,\rho,S,Q,B,C,Bt\right) = \sum_i^{N_{ch}} \Omega_i\left(M,\gamma_s,\rho,S,Q,B,C,Bt\right)$$

- The possible solution is the construction of a grid of partition functions for the different possible values of:
  1. Charges (more than 100 configurations)
  2. Mass (from $2M_{\pi^0}$ to about 10 GeV)
  3. γ_s and ρ (needed only to perform the tuning)
- The information on Ω is obtained at runtime by interpolation on M, γ_s and ρ

Free parameters and generator tuning

- The statistical model needs only 2 $(+1)$ parameters: γ_s and ρ (and the cluster low mass cut M_{cut})...
- ...but there is a strong interplay with some of HERWIG's free parameters, since MCSTHAR++ uses its clusters:
  - quark masses
  - gluon mass
  - quark and gluon virtuality cut
  - Λ_{QCD}
- All these parameters are involved into the QCD shower: they regulate the clusters mass, flavour composition and phase space distribution

For a fine tuning of the generator is necessary to understand the interplay between the two sets of parameters and make a global minimization

...but for the present...

Preliminary results @LEP

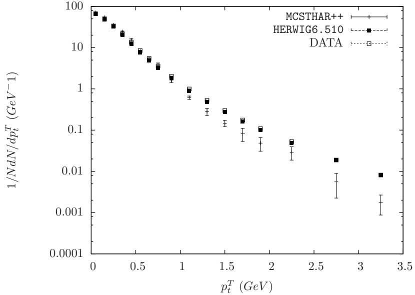
- A preliminary tuning on LEP data has been performed on MCSTHAR++'s parameters γ_S, ρ and M_C.
- The optimal parameter configuration has been obtained considering the χ^2 values for a set of event shape and single particle distributions and for the multiplicities of 41 hadrons.

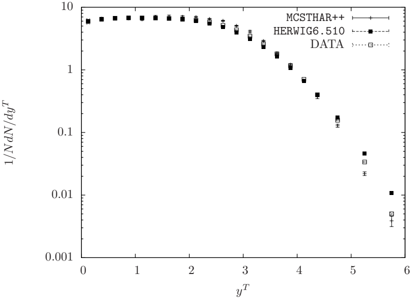
$M_C(GeV)$	γ_S	$\rho(GeV/fm^3)$	χ^2_{red} (ES)	χ^2_{red} (SP)	χ^2_{red} (PM)	χ^2_{red}
1.4	0.65	0.25	12.43	6.93	16.52	10.04
1.4	0.65	0.35	16.45	7.35	18.01	12.24
1.4	0.65	0.45	36.00	21.29	6.50	27.57
1.6	0.65	0.25	21.38	7.85	21.49	15.00
1.6	0.65	0.35	14.59	6.46	16.04	10.83
1.6	0.65	0.45	9.95	7.48	18.15	9.20
1.8	0.65	0.25	31.34	8.04	17.23	19.63
1.8	0.65	0.35	20.23	7.26	19.30	14.06
1.8	0.65	0.45	17.66	8.75	10.18	13.08
1.6	0.60	0.35	16.41	6.55	18.44	11.86
1.6	0.65	0.35	14.59	6.46	16.04	10.83
1.6	0.70	0.35	31.01	12.90	8.72	21.34
1.6	0.55	0.45	11.25	6.94	25.63	9.94
1.6	0.675	0.45	11.85	5.88	20.17	9.45
1.6	0.70	0.45	18.92	6.15	14.41	12.67

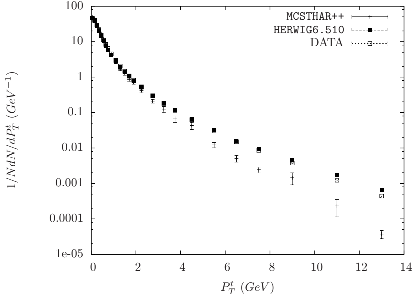
- "Best fit" parameter configuration: $M_C = 1.6\ GeV$, $\gamma_S = 0.65$ and $\rho = 0.45\ GeV/fm^3$.

Preliminary results @LEP: Event shape

- Comparison among MCSTHAR++, HERWIG6.510 and DELPHI data (Z. Phys. C **73** (1996) 11)
- $T = \max_{\vec{n}} \frac{\sum_{j=1}^{N_P} \mid \vec{p}_i \cdot \vec{n} \mid}{\sum_{j=1}^{N_P} \mid \vec{p}_i \mid}$
- $y^T = \frac{1}{2} \cdot \log \frac{E + p_T}{E - p_T}$

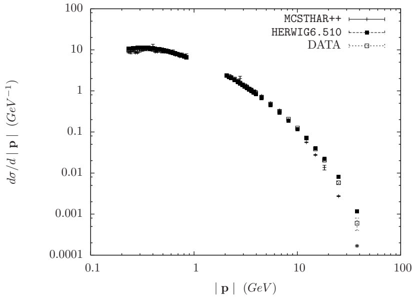




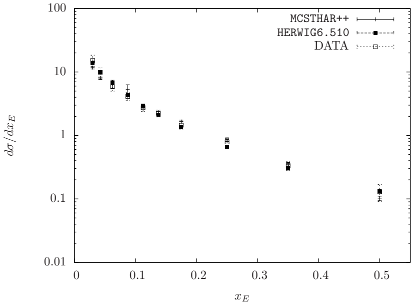


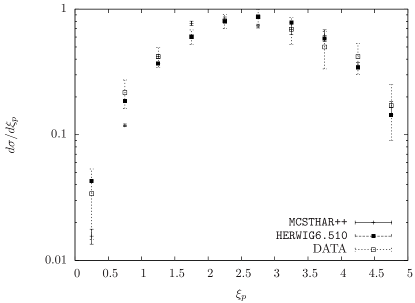
Preliminary results @LEP: Single particle

- Comparison among MCSTHAR++, HERWIG6.510 and OPAL data
  (Z. Phys. C 63 (1994) 181)
  (Eur. Phys. J. C 5 (1998) 411)



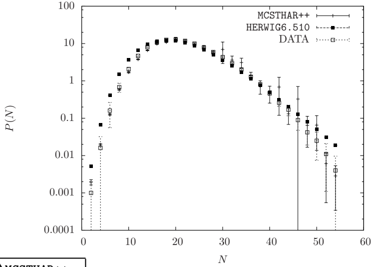
- $|\mathbf{p}| \rightarrow \pi^{\pm}$
- $\xi_p = -\log\left(2|\mathbf{p}|/\sqrt{s}\right) \rightarrow \rho^{\pm}$
- $x_E = 2E/\sqrt{s} \rightarrow \omega$





Preliminary results @LEP: Multiplicities

- Comparison among MCSTHAR++, HERWIG6.510 and LEP data
  (Eur. Phys. J. C **56** (2008) 493)
  (Z. Phys. C **53** (1992) 539)
- $P(N) \rightarrow$ Charged particle number

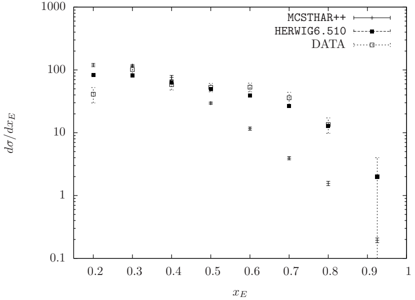


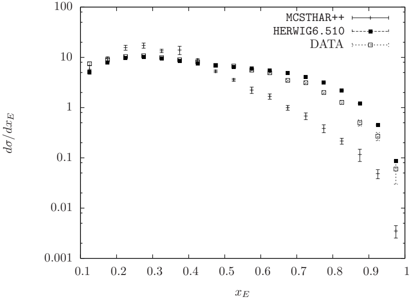
	MCSTHAR++	HERWIG6.510	LEP data	$\Delta_{\text{MCSTHAR++}}$
π^0	10.98 ± 0.13	9.56	9.61 ± 0.29	4.33
π^+	9.33 ± 0.15	8.16	8.50 ± 0.10	4.55
η	1.18 ± 0.04	0.63	1.059 ± 0.086	1.26
ρ^+	1.16 ± 0.03	0.97	1.20 ± 0.22	-0.18
ρ^0	1.42 ± 0.04	1.00	1.40 ± 0.13	0.13
ω	1.29 ± 0.03	0.97	1.024 ± 0.059	4.10
η'	0.13 ± 0.01	0.10	0.166 ± 0.047	-0.61
K^+	1.11 ± 0.02	1.05	1.127 ± 0.026	-0.31
K^0	1.07 ± 0.11	0.942	1.0376 ± 0.0096	0.30
K^{*+}	0.34 ± 0.04	0.273	0.357 ± 0.022	-0.37
K^{*0}	0.33 ± 0.02	0.274	0.370 ± 0.013	-1.92
p	0.45 ± 0.02	0.762	0.519 ± 0.018	-2.79
D^+	0.22 ± 0.01	0.287	0.238 ± 0.024	0.53
D^0	0.54 ± 0.04	0.577	0.559 ± 0.022	0.33
D_s	0.110 ± 0.009	0.112	0.116 ± 0.036	0.18
Λ_c	0.13 ± 0.01	0.036	0.079 ± 0.022	2.19

- Almost perfect agreement for $P(N)$ distribution
- $\Delta_{MCSTHAR++} \leq 3$ for the 70% of the species.
- Please, no questions about bottomed hadrons...

Preliminary results @LEP: Bad news...

- D^0 and D^* scaled energy distributions shown a wrong behavior...





- Some multiplicities shown a large disagreement...

	MCSTHAR++	HERWIG6.510	LEP data	$\Delta_{\text{MCSTHAR++}}$
ϕ	0.167 ± 0.007	0.1278	0.0977 ± 0.0058	7.16
Λ	0.128 ± 0.004	0.322	0.1943 ± 0.0038	-11.43
Σ^-	0.0233 ± 0.0007	0.0548	0.0410 ± 0.0037	-4.68
Σ^{*+}	0.0176 ± 0.0006	0.0551	0.0118 ± 0.0011	4.62
Ξ^-	0.0040 ± 0.0001	0.0391	0.01319 ± 0.00050	-17.7
Ω	$(1.09 \pm 0.04) \times 10^{-4}$	4.94×10^{-3}	$(6.2 \pm 1.0) \times 10^{-4}$	-5.11
n	0.51 ± 0.01	0.683	0.991 ± 0.054	-8.49

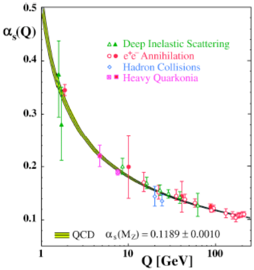
Conclusions

1. Different models are implemented in the available MC event generators
2. It is worth to have an independent model available for the hadronization:
   - MC generators are tuned on data at energy lower than the one of LHC (LEP and Tevatron)
   - The availability of independent models gives reliability to the theoretical predictions and their uncertainties
3. The statistical hadronization models have some interesting properties:
   - Small number of parameters
   - "Advanced" features: quantum statistics and interactions
4. The tuning of MCSTHAR++ with HERWIG and Herwig++ on LEP data is now a work in progress

Thank You!

Hadronization and QCD coupling constant

Why do we need a hadronization model?



- The behaviour of the QCD coupling constant is such that at $E \approx 1\ GeV$ perturbative calculations are not possible anymore
- A phenomenological model is needed to describe the hadronization process

S. Bethke, Prog. Part. Nucl. Phys. **58** (2007) 351

Main hadronization models

- Cluster model: HERWIG G. Corcella et al., JHEP 0101 (2001) 010
- String model: PYTHIA T. Sjöstrand et al., JHEP 05 (2006) 026
- Modified cluster model: SHERPA J.C. Winter et al., Eur. Phys. J. C35 (2004) 381
- Statistical model: not yet available in any MC event generator

Strong coupling constant

- In 1-loop approximation the QCD coupling constant is given by

$$\alpha_s\left(Q^2\right) = \frac{\alpha_s\left(\mu^2\right)}{1 + \alpha_s\left(\mu^2\right)\beta_0 \ln \frac{Q^2}{\mu^2}}$$

- Where $\beta_0 = \frac{33 - 2N_f}{12\pi}$

SHM transition probability

Probability to observe the decay $|\,(N_j)\,;p_1,...,p_N\rangle$

$$p\left((N_j)\,;p_1,...,p_N\right) = \frac{\frac{V^N}{(2\pi)^{3N}}\prod_{i=1}^{N}\left(2J_i+1\right)\delta^4\left(P_0-\hat{P}\right)\delta_{\mathbf{Q_0}\hat{\mathbf{Q}}_{\mathbf{f}'}}}{\sum_{(N_j')}\frac{V^{N'}}{(2\pi)^{3N'}}\left(\prod_{i=1}^{N'}\sum_{\sigma_i}\int d^3p_i\right)\delta^4\left(P_0-\hat{P}\right)\delta_{\mathbf{Q_0}\hat{\mathbf{Q}}_{\mathbf{f}'}}}$$

Probability to observe the decay $|\,(N_j)\,;p_1,...,p_N\rangle$ (Quantum statistics)

$$\prod_{j=1}^{K}\left[\sum_{r_j}\frac{\chi\left(r_j\right)^{b_j}}{N_j!}\sum_{\sigma_1,...,\sigma_{N_j}}\prod_{i_j=1}^{N_j}\frac{\delta_{\sigma_{i_j}\sigma_{r_j(i_j)}}}{(2\pi)^3}\int_A d^3x e^{-i\left(\mathbf{p}_{i_j}-\mathbf{p}_{r_j(i_j)}\right)\cdot\mathbf{x}}\right]\times$$

$$\delta^4\left(P_0-\hat{P}\right)\delta_{\mathbf{Q_0}\hat{\mathbf{Q}}_{\mathbf{f}'}}$$

- Quantum correlations give corrections of about 20% on the microcanonical weight for the single channel (6π channel and cluster mass M = 5 GeV)

Interacting hadron gas

- How to take into account the interactions between the confined hadrons?

Gas of hadrons and resonances

Retaining only the resonant part of the interaction, the microcanonical partition function is that of a gas of free hadrons and resonances with distribuited mass

References:

J. Bernstein, R. Dashen, S. Ma, Phys. Rev. **187** (1969) 1

$\Downarrow$

To include the (leading) interactions all the resonances must be included in the hadron samplings with Breit-Wigner distributed mass

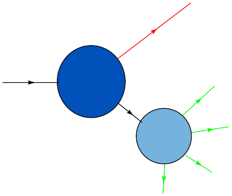
- Interactions give corrections of about -2% on the microcanonical weight for the single channel
  (4ρ channel and cluster mass $M = 4$ GeV)

MCSTHAR++: code description (III)

- Each cluster is hadronized according to the microcanonical model
- Exact conservation of
  1. Strangeness
  2. Electric charge
  3. Baryonic number
  4. Charm
  5. Beauty
  6. Energy-Momentum
- Light flavour clusters ($C = 0$ and $B = 0$): the decay channel is sampled using a multipoisson distribution

- Heavy flavour clusters: the heavy hadron is sampled using an exponential distribution

$$P(h) \propto \exp\left(-\frac{m_h}{T}\right)$$



- At this point the hadronization channel is chosen...but what about the weight???