MCSTHAR++: statistical hadronization in HERWIG

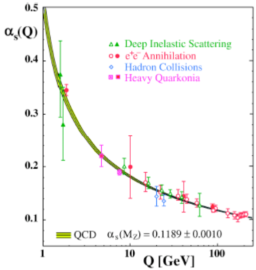
Christopher Bignamini
Università degli Studi di Pavia
INFN Sezione di Pavia
christopher.bignamini@pv.infn.it

In collaboration with
F. Becattini (FI) and **F. Piccinini (PV)**

IFAE2010
Roma
8 April 2010

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

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 $\mid f\rangle$

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

Model features and free parameters

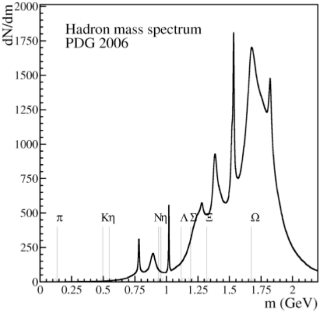
Main features

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

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:

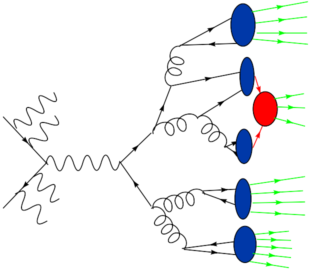
- R. Hagedorn, Nuovo Cim. Suppl. **3** (1965) 147
- F. Becattini, Z. Phys. C **69** (1996) 485
- F. Becattini, U. W. Heinz, Z. Phys. C **76** (1997) 269.
- J. Bernstein, R. Dashen, S. Ma, Phys. Rev. **187** (1969) 1

Code structure

MCSTHAR++

Monte Carlo STatistical HAdron Reaction

- MCSTHAR++ implements the statistical model in the microcanonical formulation
- It is a C++ code performing the hadronization step taking as input the clusters of Herwig and giving in output the primary hadrons

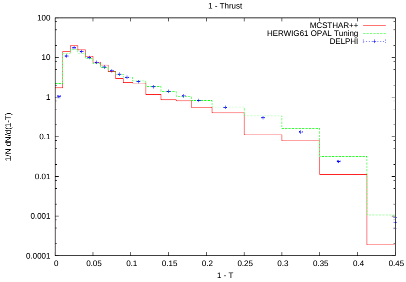


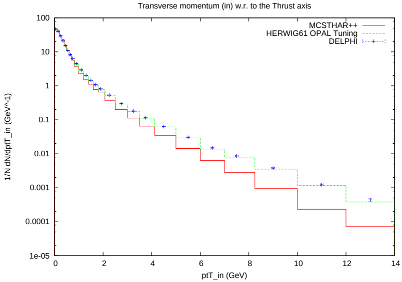
- Herwig's showers and hard scattering
- Herwig's clustering
- MCSTHAR++'s reclustering
- MCSTHAR++'s hadronization

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

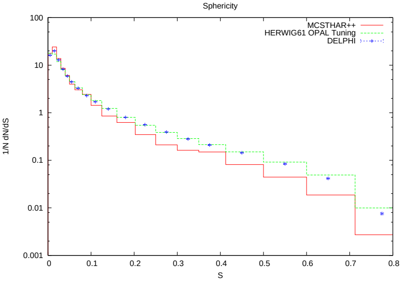
Preliminary results @LEP (I)

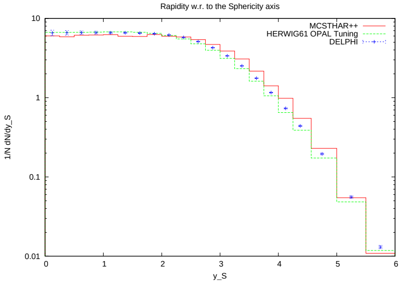
- The following results are obtained with no tuning at all of Herwig's parameters and with a "standard" choice of MCSTHAR++'s parameter:
    - $\gamma_S = 0.65$
    - $\rho = 0.35\ GeV/fm^3$
- Comparison among HERWIG6.510 + MCSTHAR++, HERWIG6.100 (OPAL tuning) and LEP data

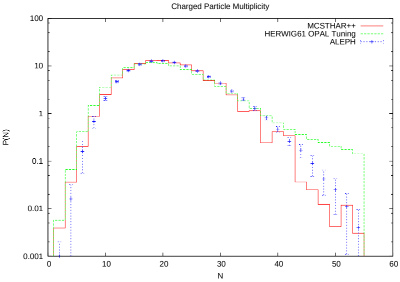




Preliminary results @LEP (II)







	MCSTHAR++	Data
All	20.93 ± 0.70	20.76 ± 0.16
γ	22.51 ± 0.68	20.97 ± 1.17
π^{+-}	18.56 ± 0.65	17.03 ± 0.16
π^0	10.71 ± 0.33	9.76 ± 0.26
ρ^{+-}	2.32 ± 0.11	2.40 ± 0.49
ρ^0	1.39 ± 0.06	1.24 ± 0.10
p	0.21 ± 0.03	1.046 ± 0.026
n	0.22 ± 0.04	0.991 ± 0.054

Conclusions

1. Phenomenological models are needed to describe the hadronization process
2. Different models are implemented in the available MC event generators
3. 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
4. The statistical hadronization models have some interesting properties:
   - Small number of parameters
   - "Advanced" features: quantum statistics and interactions
5. The tuning of MCSTHAR++ with HERWIG and Herwig++ on LEP data is now a work in progress

Thank You!

The X(3872) example (I)

- Hadronization models are needed to study some exclusive quantity
- The X(3872) has an enigmatic nature: is it a diquark-antidiquark or a $D^0 \bar{D}^{0*}$ molecular state (or something else...)?
- Assuming the molecular hypothesis, we try to simulate prompt X(3872) production at CDF and compare the upper theoretical to the lower experimental bound
- Using CDF data (CDF Coll. PRL **98** 132002 (2007)) we have

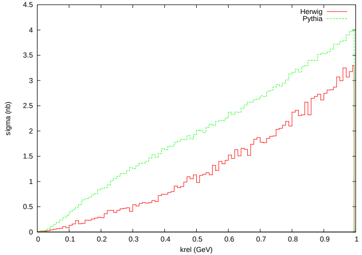
Lower experimental bound

$$\begin{aligned} \sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{min}}_{\mathrm{prompt}} &> \sigma(p\bar{p} \to X + \mathrm{All}) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-) \\ &= 3.1 \pm 0.7 \text{ nb} \end{aligned}$$

for $p_\perp(X) > 5 \text{ GeV}, |y(X)| < 0.6$

The $X(3872)$ example (II)

- We integrate the $D^0 \bar{D}^{0*}$ relative momentum distribution using `Herwig` and `Pythia` in the region $k_{rel} \leq 35$ MeV
- We get a theoretical upper limit of 0.071 nb and 0.11 nb respectively, too low by more than one order of magnitude!



- This tell us that the $D^0 \bar{D}^{0*}$ molecular hypothesis is not so good...
  C.B., B. Grinstein, F. Piccinini, A.D. Polosa, C. Sabelli Phys.Rev.Lett.103

- ...but also that it is useful to use different hadronization schemes for the simulations, to have an estimate of the uncertainty introduced by the hadronization model

X production experimental limit

- CDF measured (CDF Coll. PRL **98** 132002 (2007)) the fraction of prompt $X(3872) \to J/\psi\pi^+\pi^-$: $83.9 \pm 5.2\%$
- Using the well measured $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$

$$\frac{\sigma(p\bar{p} \to X(3872) + \mathrm{All})_{\mathrm{prompt}} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-))}{\sigma(p\bar{p} \to \psi(2S) + \mathrm{All})} = 4.7 \pm 0.8\%$$

Lower experimental bound

$$\begin{aligned} \sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{min}}_{\mathrm{prompt}} &> \sigma(p\bar{p} \to X + \mathrm{All}) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-) \\ &= 3.1 \pm 0.7 \ \mathrm{nb} \end{aligned}$$

for $p_\perp(X) > 5\ \mathrm{GeV}, |y(X)| < 0.6$

X production theoretical limit

- Hypothesis: $X(3872)$ is a bound state of two D mesons

E.S. Swanson, E. Braaten et al.

$$
\begin{aligned}
\sigma(p\bar{p} \to X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k})\rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle \right|^2 \\
&\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k})\rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle \right|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathbf{k} |\psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\text{max}}_{\text{prompt}}
\end{aligned}
$$

- $\mathbf{k}$ is the rest-frame relative 3-momentum between the D and D^*
- $|\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2$ can be computed with MC simulations
- $\mathcal{R}$ has to be given with a reasonable conservative Ansatz for the bound state wave function (we use a simple gaussian form)

Strong coupling constant

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

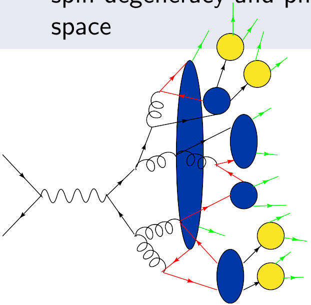
$$\alpha_s\left(Q^2\right) = \frac{\alpha_s\left(\mu^2\right)}{1 + \alpha_s\left(\mu^2\right)\beta_0 \ln \frac{Q^2}{\mu^2}}$$

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

Standard hadronization models (I)

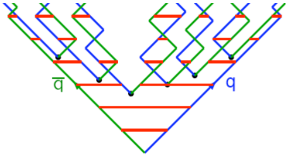
Cluster model

- Implemented in Herwig
- 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

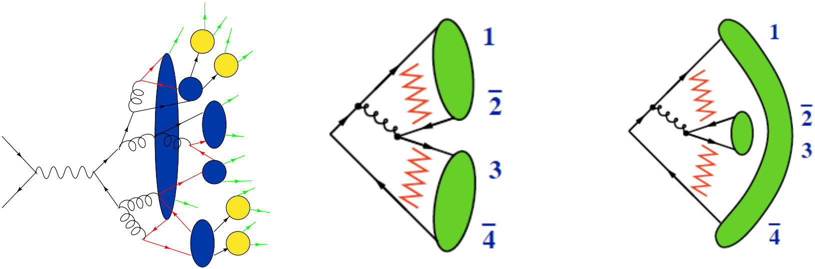
- Implemented in Pythia
- A color string is supposed to connect final state quarks, antiquarks and gluons (linear potential)
- Hadrons come from $q\bar{q}$ produced from the vacuum via string fragmentation



Standard hadronization models (II)

Modified cluster hadronization model

- Implemented in Sherpa
- Similar to the "standard" cluster model of Herwig, with some important extensions:
- Soft color-reconnection effect via the inclusion of non-planar diagrams, with relative suppression $\propto \frac{1}{N_C^2}$
- The spin information of the diquarks is accounted throughout the model
- The number of basic cluster species is enlarged (four-quark cluster)



The microcanonical hypothesis

Microcanonical description

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

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

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

Main features

- Bose-Einstein and Fermi-Dirac correlations $\Longleftrightarrow \mid h_V\rangle, \mid f\rangle$
- Interactions among the hadrons $\Longleftrightarrow p'_f \propto \int \prod dm BW(m) p_f$

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

$$C(Q) = \frac{\frac{dN\left(\pi^+\pi^+ + \pi^-\pi^-\right)}{dQ}}{\frac{dN\left(\pi^+\pi^-\right)}{dQ}}$$

$$C'(Q) = \frac{C(Q)}{C(Q)_{NoBEC}}$$

Strangeness suppression and free parameters

- To reproduce the observed multiplicities of strange particles a phenomenological parameter γ_s is included in the partition function

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

About 15 parameters to fit the multiplicities of 25 light quark hadrons @ LEP

HERWIG

About 7 parameters related to the tune of particle multiplicities

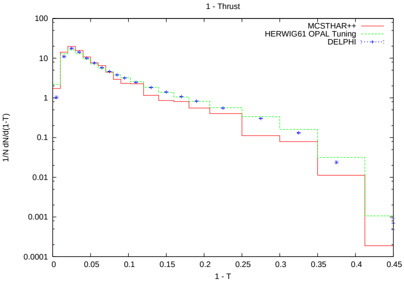
Free parameters and generator tuning

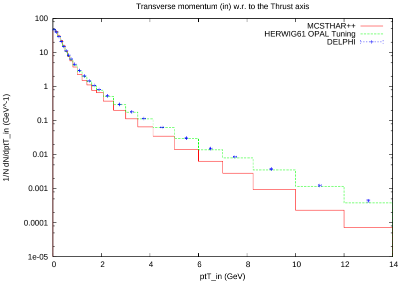
- The statistical model needs only 2 (+1) parameters: γ_s and ρ (and the cluster low mass cut M_{cut})...
- ...but there is a strong interplay with some of Herwig's free parameters, since MCSTHAR++ uses its clusters:
  - quark masses
  - gluon mass
  - quark and gluon virtuality cut
  - Λ_{QCD}
- All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

Distributions@LEP: Thrust related observables

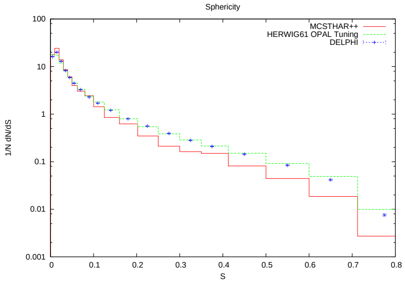
- Comparison among HERWIG6.510 + MCSTHAR++, HERWIG6.100 and LEP data

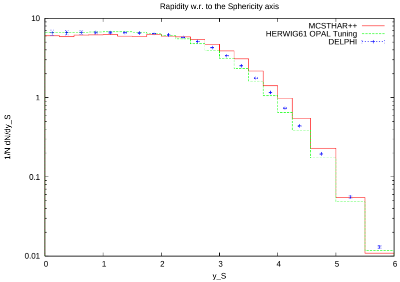




- $T = \max_{\vec{n}} \frac{\sum_{j=1}^{N_P} | \vec{p}_i \cdot \vec{n} |}{\sum_{j=1}^{N_P} | \vec{p}_i |}$

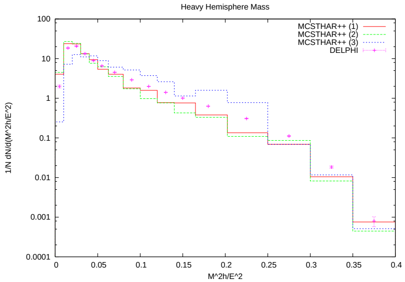
Distributions@LEP: Sphericity related observables

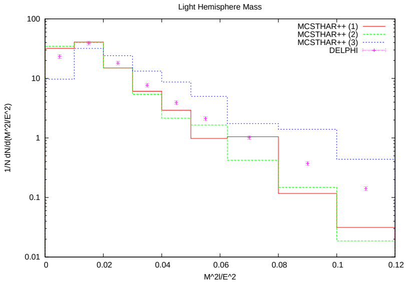




- $M^{\alpha\beta} = \sum_{j=1}^{N_P} p_i^\alpha p_i^\beta \qquad \lambda_1 \geq \lambda_2 \geq \lambda_3 \qquad \lambda_1 + \lambda_2 + \lambda_3 = 1$
- $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
- $y_S = \frac{1}{2} \cdot \log \frac{E + p_S}{E - p_S}$

Distributions@LEP: free parameters dependence

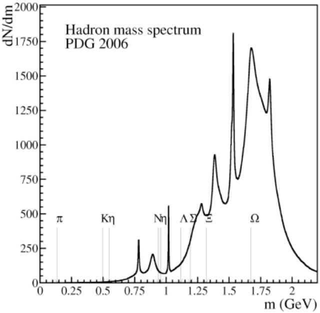




- Parameter sets:
  1. $\gamma_s = 0.65 \quad \rho = 0.35\ GeV/fm^3$
  2. $\gamma_s = 0.5 \quad \rho = 0.2\ GeV/fm^3$
  3. $\gamma_s = 1.0 \quad \rho = 0.5\ GeV/fm^3$
- $$\frac{M_h^2}{E^2} = \frac{1}{E^2} \max\left(\left(\sum_{\vec{p}_j \cdot \vec{n}_T > 0} p_j\right)^2, \left(\sum_{\vec{p}_j \cdot \vec{n}_T < 0} p_j\right)^2\right)$$

Hadron mass spectrum and Hagedorn model

- In the Statistical Bootstrap Model the clusters are real resonances
- They decay into hadrons in function of the available phase space
- The mass spectrum of these objects (clusters/resonances) can be obtained using a bootstrap equation



$$\frac{dN}{dm} \propto m^a \exp\left(\frac{m}{T}\right) \qquad T \approx 160\ MeV$$

R. Hagedorn, Nuovo Cim. Suppl. **3** (1965) 147