Statistical hadronization in HERWIG
Preliminary results

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Outline

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1. Introduction
2. The statistical hadronization model
3. MCSTHAR++ - Preliminary results
4. Conclusions

Outline

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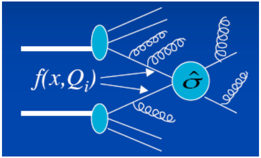
Part I

Introduction

High energy process evolution and factorization theorem

- An high-energy event in a Monte Carlo generator is built on the following elements:

1. Parton distribution functions and matrix element
2. Parton shower algorithm
3. Underlying event description
4. Hadronization models, ...



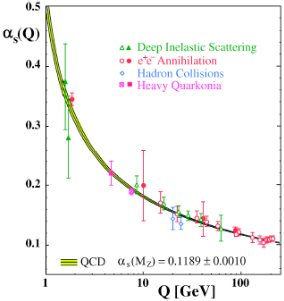
Factorization theorem

$$\frac{d\sigma}{dx} = \sum_{j,k} \int f_j\left(x_1, Q_i\right) f_k\left(x_2, Q_i\right) \frac{d\hat{\sigma}_{jk}\left(Q_i, Q_f\right)}{d\hat{x}} F\left(\hat{x} \rightarrow x; Q_i, Q_f\right) \ldots$$

- $F\left(\hat{x} \rightarrow x; Q_i, Q_f\right)$ Transition function from the partonic to the observable hadronic states

The strong coupling constant

- The behaviour of the QCD coupling constant is such that at $E \approx 1\ GeV$ perturbative calculations are no more possible



A phenomenological model is needed to describe the hadronization process

References:

S. Bethke,

Prog. Part. Nucl. Phys. **58** (2007) 351

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

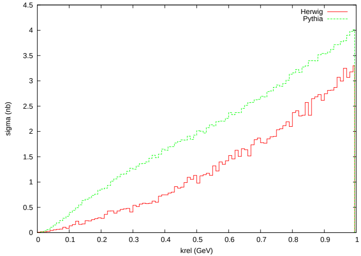
Lower experimental bound

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

for $p_\perp(X) > 5$ 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 arXiv:0906.0882

- ...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

Phenomenological models

- Cluster fragmentation model, implemented in HERWIG and Herwig++
- String fragmentation model, implemented in PYTHIA and PYTHIA8
- Many other variants...
- Statistical hadronization model, not yet implemented in any official release of the MC codes

MCSTHAR++

Monte Carlo STatistical HAdron Reaction

Part II

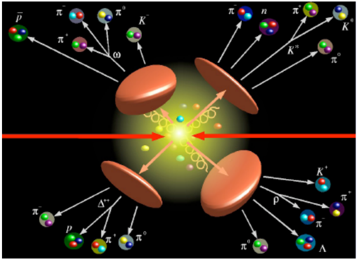
The statistical hadronization model

Statistical hadron production

- 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

$$P, J, I, I_3, Q, \ldots$$

is colour neutral and hadronizes according to a pure statistical law



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.

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 $\mid f\rangle$

$$p_f \propto \langle f \mid P_i P_V P_i \mid f \rangle$$

- $P_i = P_P P_{Q,S,B}$
- $P_V = \sum_{h_V} \mid h_V\rangle\langle h_V \mid$

Microcanonical partition function

$$\sum_f p_f \propto \sum_f \langle f \mid P_i P_V P_i \mid f \rangle = \Omega$$

- Bose-Einstein and Fermi-Dirac correlations are included

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

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

Part III

MCSTHAR++ - Preliminary results

Code description and projects

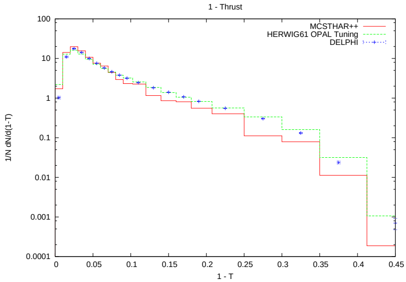
- MCSTHAR++ implements the statistical model in the microcanonical formulation as described in: F. Becattini, L. Ferroni, Eur. Phys. J. C38, 2004.
- The code is written in C++, using an Object Oriented framework, accordingly to the new MC event generators (Herwig++, PYTHIA8, SHERPA, ...)
- We are working on two projects:
  1. MCSTHAR++ + HERWIG
     Collaboration between PV (C.B. and F. Piccinini) and FI (F. Becattini)
  2. MCSTHAR++ + Herwig++
     Work supported by the MCnet network, in collaboration with the Karlsruhe team of developers of Herwig++ (S. Gieseke)

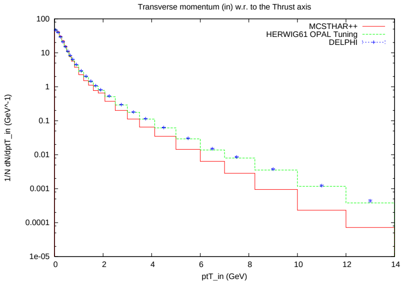
Preliminary results

- Before starting to tune the generator on LEP data we have made some explorative runs
- The results shown in the next slides are obtained with no tuning at all of Herwig parameters involved in the hadronization process:
  - quark masses
  - gluon mass
  - quark and gluon virtuality cut
  - Λ_{QCD}
- While for MCSTHAR++ parameters we have chosen the (standard) values
  - $\gamma_S = 0.65$
  - $\rho = 0.35\ GeV/fm^3$
  - $M_{cut} = 1.4\ GeV$
- No interactions and quantum statistics included
- For a fine tuning of the generator a study of the interplay between the two sets of parameters is needed

Distributions@LEP: Thrust related observables

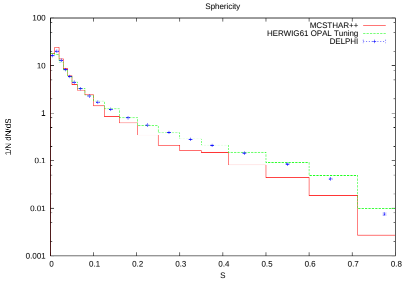
- Comparison among HERWIG6.510 + MCSTHAR++, HERWIG6.100 and LEP data

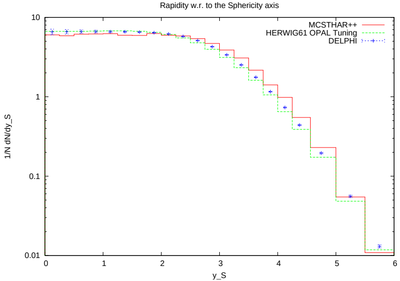




- $T = \max_{\vec{n}} \dfrac{\displaystyle\sum_{j=1}^{N_P} \mid \vec{p}_i \cdot \vec{n} \mid}{\displaystyle\sum_{j=1}^{N_P} \mid \vec{p}_i \mid}$

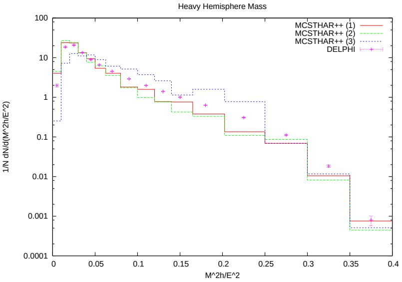
Distributions@LEP: Sphericity related observables

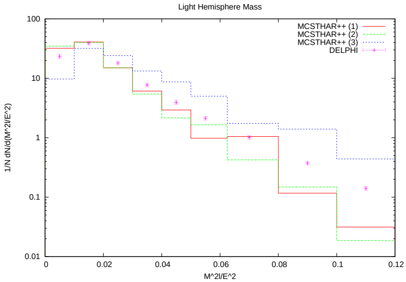




- $M^{\alpha\beta} = \sum_{j=1}^{N_P} p_i^\alpha p_i^\beta \qquad \lambda_1 \geq \lambda_2 \geq \lambda_3 \qquad \lambda_1 + \lambda_2 + \lambda_3 = 1$
- $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
- $y_S = \frac{1}{2} \cdot \log \frac{E + p_S}{E - p_S}$

Distributions@LEP: free parameters dependence

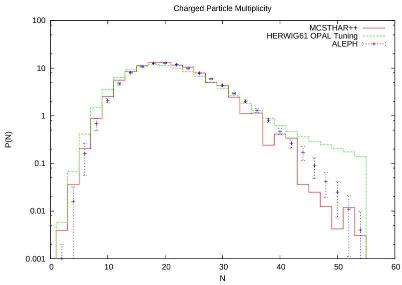




- Parameter sets:
  1. $\gamma_s = 0.65 \quad \rho = 0.35\ GeV/fm^3$
  2. $\gamma_s = 0.5 \quad \rho = 0.2\ GeV/fm^3$
  3. $\gamma_s = 1.0 \quad \rho = 0.5\ GeV/fm^3$
- $$\frac{M_h^2}{E^2} = \frac{1}{E^2} \max\left(\left(\sum_{\vec{p}_j \cdot \vec{n}_T > 0} p_j\right)^2, \left(\sum_{\vec{p}_j \cdot \vec{n}_T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

Multiplicities@LEP

- In spite of a "good" agreement (it is just the first run after all...) for the inclusive distributions studied and in particular for the charged particle number distribution there are some problems with the single particle multiplicities:



	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
D^{+-}	0	0.187 ± 0.02
D^0	0	0.462 ± 0.02

Corrections and next steps

- Independent production of open charm and open bottom hadrons (charm and beauty charge conservation) with probability density

$$P \propto exp(-m/T)$$

- Creation of baryonic clusters by Herwig to enhance the production of baryons during the hadronization step
- Inclusion of interactions and quantum statistic in the partition function calculation
- Recursive calculation of the partition function to save computational time

$$\Omega(M, V, \mathbf{Q}) \propto \int_0^1 dx \; x \sum_j (K_j(x) \; \Omega((M - m_j)x, V, \mathbf{Q} - \mathbf{q_j}))$$

Part IV

Conclusions

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:
   - Small number of phenomenological parameters
   - MC generators are tuned on data at energy lower than the one of LHC
   - The availability of independent models gives reliability to the theoretical predictions and their uncertainties
4. MCSTHAR++ is ready to be tuned on LEP data with HERWIG and Herwig++

Thank You!

Part V

Backup slides

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 $p_\perp(X) > 5$ 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 $\beta_0 = \frac{33 - 2N_f}{12\pi}$