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Review of hadron production rate measurements in $e^{+}e^{-}$ annihilation

E. C. Berg and C. D. Buchanan

UCLA Physics Department, 405 Hilgard Avenue, Los Angeles, CA 90095

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ABSTRACT

We present a comprehensive review of hadron production rate measurements in e+e- annihilation experiments at 10 (continuum), 29, and 91 GeV for (including antiparticles) π^{0}, $\pi^{\pm}$, η, η', $K^{\pm}$, K^{0}, ρ^{0}, $K^{*\pm}$, K^{*0}, ϕ, $p^{\pm}$, Λ, Ξ^{-}, Δ^{++}, Σ^{*+} or Σ^{*-}, Ξ^{*0}, Ω^{-}, and all charged particles. We respond to the need for a summary of production rate measurements from e+e- colliders in the 25-40 GeV energy region, where data are no longer being accumulated, and include for comparison results at 10 and 91 GeV where data are still being produced. A detailed reference tabulation is included to provide an archive of published measurements. Rates quoted in refereed journals and institutional preprints are combined, taking into account inconsistent measurements and estimations of common systematic errors. To facilitate comparisons with hadronization model predictions, estimations of uncertainties from decay rates are provided as well.

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I. INTRODUCTION

Accurate measurement of the production rates (as well as the distributions and correlations) of various flavored mesons and baryons in electron-positron annihilations over a range of center-of-mass energies provides very valuable physical information. In particular, e+e- interactions provide a cleaner environment than lepton-hadron or hadron-hadron interactions for studying the fundamentals of the hadronization process: how a parton-colorfield system (to use QCD-based language) evolves into a system of hadrons. For example, one knows, both intuitively and by direct measurement, that heavier hadrons are produced less often than lighter hadrons. Various mechanisms have been proposed to describe this (see for example Ref. [1]). Detailed information on various flavored meson and baron production rates provides tests of these models as one attempts to understand this evolution into hadrons.

Hadron production rates have been measured at many of the particle accelerators and associated detectors which have been constructed in the last 30 years. Table I reviews the energy and running status of relevant e+e- colliders, the type where hadron production is simplest. Note that since both PEP and PETRA are now turned off, no more data is expected around $E_{cm} \sim 29$ GeV. In contrast, continued new data is expected at E_{cm} ♠ 10 GeV (CLEO), ~ 60 GeV (TRISTAN), and ~ 91 GeV (LEP, SLC).

We present here a comprehensive compilation of results at E_{cm} ♠ 10 GeV (continuum), 29 GeV, and 91 GeV to be used as a resource for future studies. We have attempted to combine and quote uncertainties in a reasonable, though somewhat subjective way, so as to make model-to-data comparisons as easy and accurate as possible. We also present extensive reference information in order to provide a comprehensive archive of the subject.

II. CREATING WORLD AVERAGES

Reasonably combining results from different and overlapping experiments involves several areas where careful subjective judgment must be used in order to form an appropriate world average and its associated uncertainty. These include: what references to include and exclude, how to shift nearby results to a common center-of-mass energy, how to handle common systematics in data samples from the same detector and in similar analyses, and how to handle the results when measurements are inconsistent. The world average results of our work are presented in Tables II (10 GeV continuum), III (29 GeV), and IV (91 GeV) for, including antiparticles: π□, $\pi^{\pm}$, η, η', $K^{\pm}$, K□, ρ□, $K^{*\pm}$, K^{*}□, ϕ, $p^{\pm}$, Λ, Ξ^{-}, Δ^{++}, Σ^{*+} or Σ^{*-}, Ξ^{*}□, Ω^{-}, and all charged particles.

Tables V-XXII present a comprehensive archival survey of published production rate measurements for each particle flavor. As such, we tabulate all publications which report a rate measurement. A subset of these is then used to form a world average. Three groups of references can be identified. The first, the group we use to form the world average, consists of independent measurements which have been published in refereed journals or national laboratory preprints (footnoted by laboratory). The second group contains other publications which report measurements such as conference proceedings or Ph.D. theses which are not used in the world average. We do not use these because results from conference proceedings are often preliminary and subject to change and results from Ph.D. theses are not always agreed to by the experiment collaboration. The third category is a collection of related references which do not report rate measurements. In our summary section, we discuss some of the particle production rates where unpublished or preliminary results might substantially influence the world averages or the physical inferences from them.

Tables V-XXII list production rate measurements for each particle in the following format: Each line consists of publication year; collaboration name; reference number (see the Appendix: Key to Tables); quoted rate (#/event) and uncertainty;

experimental center-of-mass energy (GeV); rate (#/event) and uncertainty scaled to either 10, 29, or 91 GeV; and an identification number (#) that shows which entries are results from the same dataset (a question mark here indicates that there may be overlap between measurements). Measurement entries are ordered by experiment and date. Entries which are used in forming the world averages are indicated by a ✔ mark and are required to be close to the E_{cm} they are scaled to and to be independent of the other entries (in general the most recent result is used). In all cases, rates are either quoted or adjusted to include all pions and protons from K**Error!**) and Λ□ decays.

The quoted uncertainty is either the total uncertainty or the statistical then systematic uncertainty. A question mark indicates that the publication neglected to specify if systematic uncertainties were included, whereas a hyphen indicates that the article specified that the single quoted uncertainty includes systematics. The rates are scaled by a factor of $ln(E_{cm}/2M_{hadron})$ as is predicted by QCD scaling violation [2], with an uncertainty of ±30% of the deviation from 1.0. Scaling factors are typically around 4%, which is a very good approximation among measurements at similar energies. The mass used for the scaling of the $N_{charged}$ measurements (193.4 MeV) was found to be uniform from 10 to 91 GeV by summing the $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ contributions. The tables are broken into sections corresponding to measurements around 10, 29, and 91 GeV center-of-mass energy. These tables are the end product of a thorough search of the SPIRES high energy physics database at SLAC for references prior to May, 1995. Additionally, our search included the citations listed in articles up through October, 1993 which quoted rates. Each table concludes with a list of additional references which we could not obtain as well as a list of related references, typically ones which did not quote a rate measurement. A cross reference table is provided at the end (Table XXIII).

In determining the world averages, we begin with a simple weighted average, performed in the usual way with

$$\bar{x} = \frac{\sum_i x_i w_i}{\sum_j w_j} \tag{1}$$

and

$$\sigma_{\bar{x}}^2 = \sum_i \left(\frac{\partial \bar{x}}{\partial x_i}\sigma_i\right)^2 + 2\sum_{ik}^{i>k} \frac{\partial \bar{x}}{\partial x_i}\frac{\partial \bar{x}}{\partial x_k}\sigma_{ik}^2 = \frac{\sum_i (\sigma_i w_i)^2}{\left(\sum_j w_j\right)^2} \Rightarrow \frac{1}{\sum_j w_j} \tag{2}$$

where w_j is the inverse-squared of the uncertainty quoted for the j^{th} measurement .

In order to improve the accuracy of the world average and its uncertainty, we then approximately account for the common systematic errors among measurements from the same detector and from similar analysis techniques. The direct and rigorous approach to this would derive a generalized equation for $\bar{x}$ by minimizing

$$\chi^2 = (x_i-\bar{x})(\sigma_{ij}^2)^{-1}(x_j-\bar{x}) . \tag{3}$$

The corresponding formula for $\sigma_{\bar{x}}{}^2$ would follow from $\bar{x}$ by using Equation 2. To avoid the difficulty of minimizing this χ^2, a weighted average is calculated for measurement subsets from the same detector as follows: (1) A common systematic fractional uncertainty is removed from each measurement in quadrature (assumed to be 60% of the smallest fractional systematic error). (2) A weighted average is calculated using the remaining systematic and statistical uncertainties. (3) The common fractional systematic uncertainty is re-included for the detector. The subsets from different detectors are then combined using a similar process. Here, 40% of the smallest quoted fractional systematic error is assumed to be due to the analysis technique. We emphasize that this approach represents a subjective approximate judgment on our part. However, to leave out such a treatment can lead to a seriously underestimated uncertainty in situations where there are many measurements. Typically this treatment of common systematic errors increases the overall uncertainty by 0% to 20%, depending on the number of measurements. This technique ensures that the uncertainty on the total ensemble of measurements is never less than 40% of the smallest systematic uncertainty.

Next, we consider the fact that published uncertainties may be poor estimates of the actual uncertainties. This is only a significant problem when the quoted error is too small, of course. To account for this effect, the square root of the total χ^2 per degree of freedom is calculated after taking common systematics into account;

$$\sqrt{\chi^2/(n-1)} \quad = \quad \sqrt{\sum_i \left[(x_i-\overline{x})/\sigma_i\right]^2/(n-1)} \quad . \tag{4}$$

If the result is greater than 1.0 then the uncertainty of that world average is increased by this factor. It should be noted that this use of the goodness-of-fit information to increase the world average's uncertainty is an approximate way of combining a distribution of measurements and uncertainties into an effective single measurement.

After incorporating these effects, we generate Tables II-IV which, as discussed above, summarize our results by particle and by E_{cm}. The column labeled *World Average* gives our result for the combined world average and its overall uncertainty. Typically, we quote the overall uncertainty to two significant digits. Note that in some cases, where many measurements come from the same detector, the world average is slightly changed by taking into account common systematics. The column labeled # is the number of measurements used to form the world average. The column labeled *Basic Uncertainty* is the uncertainty for the simple weighted average. The column labeled *Syst Adjusted* (uncertainty) is the uncertainty after adjusting for common detector and analysis systematics. The next column labeled *χ^2 Factor* is the value calculated in Equation 4 which is a measure of the consistency among measurements. It is used to increase the world average uncertainty (where needed) and leads to the final overall uncertainty quoted in the *World Average*.

If an experimental world average production rate for a particular hadron is to be compared to a model prediction, then the comparison should also include the uncertainty in the model prediction coming from the uncertainty in decay fractions presumed in the model. For example, in the Lund JETSET7.3 model [3] approximately 17% of all ϕ's at 29

GeV come from decays of D_s, where inclusive D_s ∅ φ accounts for ~ 13% ±4% of all D_s decays. Thus the predicted φ rate is uncertain from this D_s decay mode by: ±4% divided by 13% times 17% = 5%. As an aid for such comparisons, we have included a column in Tables II-IV giving a crudely estimated uncertainty from decay tables to be included (in quadrature for small errors) in such data-versus-model comparisons.

III. SUMMARY AND FUTURE

We have combined the rate measurements of various flavored hadrons made at E_{cm} ♠ 10 GeV (continuum), 29 GeV, and 91 GeV to form world averages and their associated uncertainties. Our procedure has included judgments on what independent measurements to include, how to extrapolate results to nearby center-of-mass energies, how to handle common systematic uncertainties, and how to handle inconsistent measurements.

The ideal situation for the construction of a believable, useful set of world averages is one in which there are three or more measurements in refereed journals or national laboratory preprints, each with good precision and in reasonable agreement, for each particle at each energy. One would like to see additional careful measurements where only one relevant measurement exists or where the measurements are significantly different. We note from Tables II - IV that there are several cases (mostly at 91 GeV and 10 GeV continuum) where only one measurement has been made or where the χ^2 factor is greater than 2.0. Confidence in the results, therefore, would be significantly improved by additional measurements in these cases.

Presently, the most important situations where additional measurements would be useful are in the spin $\frac{3}{2}$ baryons: $\Sigma^{*\pm}$, Ξ^{*}□, and Ω^- (see Tables XIX-XXI). For $\Sigma^{*\pm}$ there is one measurement at 10 GeV, one published measurement at 29 GeV, and two published measurements at 91 GeV. For Ξ^{*}□, there is one measurement at 10 GeV, two weak (uncertainty > 50%) measurements at 29 GeV, and two marginally incompatible measurements (χ^2 ♠ 2.0/one degree of freedom) at 91 GeV. The Ω^- measurements, which are very low rate and rather difficult, exhibit the most inconsistencies. There is one weak measurement at 10 GeV (0.00072±.00038 by ARGUS [4]). At 29 GeV, there are two weak and marginally incompatible results (0.0140±.0072 by Mark II and 0.0042±.0026 by TPC/Two-Gamma [5]). At 91 GeV, the only published Ω^- result is 0.0050±.0015 from OPAL [6]; however, ALEPH reported 0.0012±.0005 in a paper contributed to the Dallas conference of 1992 and OPAL reported a revised value of 0.0028±.0008±.0003 in a paper contributed to the Glasgow conference of 1994 [6]. We also note (see Tables XIX and XXI) a recent TPC/Two-Gamma Ph.D. thesis with low values for $\Sigma^{*\pm}$ and for Ω^- at 29GeV [5]. We understand that there are additional ongoing analyses at LEP which should help clarify the situation for $\Sigma^{*\pm}$, Ξ^{*}□, and Ω^- at 91 GeV.

We hope and anticipate that the world averages derived from our comprehensive reference search (see Tables II-IV) will provide a reasonable basis for detailed comparisons with predictions of hadronization models, leading to improved inferences to be made about the underlying physics.

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TABLE CAPTIONS:

TABLE I. Summary of all high energy e^+e^- collider experiments [various references in the APPENDIX; ASP Collaboration, A. S. Johnson *et al.*, in *Proceedings of the 22nd Rencontre De Moriond, Gif-sur-Yvette, 1987,* p. 119; BES Collaboration, M. S. Chanowitz *et al.*, Lawrence Berkeley Laboratory Report No. LBL-26484, 1989; MARK II Collaboration, A. Petersen *et al.*, Phys. Rev. D **37**, 1 (1988); SLD Collaboration, realtime beam monitor, Stanford Linear Accelerator Center, Stanford, CA 1993; VEPP Collaboration, S. I. Dolinsky *et al.*, Phys. Rep. **202**, 99 (1991)].

TABLE II. Summary table of rates and errors at 10 GeV (continuum).

TABLE III. Summary table of rates and errors at 29 GeV.

TABLE IV. Summary table of rates and errors at 91 GeV.

TABLE V. π□ production rate measurements.

TABLE VI. $\pi^{\pm}$ production rate measurements.

TABLE VII. η production rate measurements.

TABLE VIII. η' production rate measurements.

TABLE IX. $K^{\pm}$ production rate measurements.

TABLE X. K□ production rate measurements.

TABLE XI. ρ□ production rate measurements.

TABLE XII. $K^{*\pm}$ production rate measurements.

TABLE XIII. K^{*}□ production rate measurements.

TABLE XIV. ϕ production rate measurements.

TABLE XV. $p^{\pm}$ production rate measurements.

TABLE XVI. Λ production rate measurements.

TABLE XVII. Ξ^- production rate measurements.

TABLE XVIII. Δ^{++} production rate measurements.

TABLE XIX. Σ^{*+} and Σ^{*-} production rate measurements.

TABLE XX. Ξ^{*}□ production rate measurements.

TABLE XXI. Ω^- production rate measurements.

TABLE XXII. All charged particles' production rate measurements.

TABLE XXIII. Cross referencing table. Overlapping datasets are grouped in '[ ]'.

Table I.

Collaboration	Accelerator	Location	E_{cm} (GeV)	Status
PSI	ADONE	Frascati, Italy	1.4-3.1	on
BES	BEPC	China	2.2-2.8	on
SPEAR	SPEAR	SLAC, California, USA	4-7	off
VEPP	VEPP	Novosibirsk, Russia	0.5-1.4	on
ARGUS	DORIS	DESY, Hamburg, Germany	9-12	off
PLUTO	DORIS	DESY, Hamburg, Germany	9-12	off
CLEO	CESR	Cornell, New York, USA	9-11	on
CUSB	CESR	Cornell, New York, USA	9-11	off
DELCO	PEP	SLAC, California, USA	29	off
HRS	PEP	SLAC, California, USA	29	off
MAC	PEP	SLAC, California, USA	29	off
ASP	PEP	SLAC, California, USA	29	off
MARK II	PEP	SLAC, California, USA	29	off
TPC/Two-	PEP	SLAC, California, USA	27.4-29	off
CELLO	PETRA	DESY, Hamburg, Germany	12-47	off
JADE	PETRA	DESY, Hamburg, Germany	12-47	off
MARK J	PETRA	DESY, Hamburg, Germany	12-47	off
PLUTO	PETRA	DESY, Hamburg, Germany	12-47	off
TASSO	PETRA	DESY, Hamburg, Germany	12-47	off
AMY	TRISTAN	KEK, Tsukuba, Japan	50-64	on
TOPAZ	TRISTAN	KEK, Tsukuba, Japan	50-64	on
VENUS	TRISTAN	KEK, Tsukuba, Japan	50-64	on
SLD	SLC	SLAC, California, USA	89-93	on
MARK II	SLC	SLAC, California, USA	89-93	off
ALEPH	LEP	CERN, Geneve,Switzerland	88-95	on
DELPHI	LEP	CERN, Geneve,Switzerland	88-95	on
L3	LEP	CERN, Geneve,Switzerland	88-95	on
OPAL	LEP	CERN, Geneve,Switzerland	88-95	on

Table XXIII.

Particle	Ecm	References
π^o	10 GeV	20,34,[37,38],83
	29 GeV	28,83,86,[156,165],168,[182,183]
	91 GeV	56,[87,90]
$\pi^\pm$	10 GeV	17,34,44,154,163
	29 GeV	[154,163,168],162,[174,183],189
	91 GeV	117
η^o	10 GeV	15,20,37,38
	29 GeV	28,[73,74],[81,83,86],108
	91 GeV	4,9,90
η'	10 GeV	21,24,37
	29 GeV	108
	91 GeV	4,9
$K^\pm$	10 GeV	17,34,44,163
	29 GeV	[154,162,163,168],[174,183],184,189
	91 GeV	57,117
K^o	10 GeV	17,34,39,79,133,[163,171]
	29 GeV	29,[70,77],79,85,102,111,133,145,[156,163,171],[177,183],194
	91 GeV	7,51,55,90,111,[116,1245],134
ρ^o	10 GeV	23,34
	29 GeV	[64,76],82,[159,168],190
	91 GeV	10,[53,55]
$K^{*\pm}$	10 GeV	23,34
	29 GeV	71,82
	91 GeV	10,[51,55],122
K^{*o}	10 GeV	23,34
	29 GeV	29,[64,76],171,[177,183],190
	91 GeV	53,[119,125]
ϕ^o	10 GeV	19,23,34
	29 GeV	[175,183],190
	91 GeV	[119,125]
$p^\pm$	10 GeV	17,34,44,45,[154,163]
	29 GeV	80,[154,161,162,163,168],[174,178,183],189
	91 GeV	57,117
Λ^o	10 GeV	16,34,163
	29 GeV	29[66,70]80,84,103,111[163,167,170][147,154][178,180,183][191,192,193]194
	91 GeV	7,51,54,90,111,120,123,134
Ξ^-	10 GeV	16,34
	29 GeV	72,85,[106,109],[155,156,163,167,170],[178,179,183,184],[191,192,193],194
	91 GeV	51,58,120,123
Δ^{++}	10 GeV	18
	29 GeV	158
	91 GeV	
$\Sigma^{*\pm}$	10 GeV	16
	29 GeV	72,158,[167,170],[183,184],194
	91 GeV	58,120,123
Ξ^{*}□	10 GeV	16
	29 GeV	[106,109],[191,192,193]
	91 GeV	58,120,123
Ω^-	10 GeV	16
	29 GeV	[107,109],167,[183,184],[191,192,193],194
	91 GeV	5,120,123
Ncharge	10 GeV	22,31,79,91,[132,133],144,[157,169]
	29 GeV	[62,65],67,78,79,85,104,132,144,[157,169],173
	57 GeV	11
	91 GeV	[2,3],48,49,87,89,[110,112],115,118