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STUDY OF HEAVY QUARKS AT THE CERN ANTIPROTON–PROTON COLLIDER1)

STRAUSS, J.,2) Vienna

The present knowledge about the top-, bottom-, and possible 4-th generation quarks as obtained at the Cern Collider is summarized. The prospects for discovering top in the year 1989 or beyond are discussed.

I. INTRODUCTION

The discovery of the *W* and *Z* bosons [1], and the study of their production and decay properties at the Cern Collider has verified the main expectations of the Standard Model. Apart from precision tests that will soon become feasible at LEP, there remain some questions concerning the Standard Model, which could be easily answered if relevant data from a high energy hadron collider existed. Since 1983, one of most popular of these questions is: What is the mass of the top quark? There is no doubt that LEP will bear on this question (even if the top mass may turn out to be beyond the kinematical reach of LEP) because electro-weak radiative corrections [2] are proportional to m_t^2. If top should indeed be discovered in such an indirect way, then the great news will be yet harder to explain to non-specialists than any previous relevant result of experimental high energy physics. A similar comment also applies to the indirect information on m_t from $(B^0, \bar{B}^0)$ mixing [3], which at present seems to imply $m_t > 45$ GeV (most probably $m_t = 80 - 100$ GeV), notwithstanding the unpleasant fact that it seems very hard to imagine, at present, how the data on $(B^0, \bar{B}^0)$ mixing could be substantially improved.

In this article, I discuss the present situation in the search for the direct production of the top, as well as the potentialities of the anticipated searches in the not-too-distant future: UA2 and UA1 at the improved Cern Collider (ACOL or AAC), and CDF at the TEVATRON. At the end of the article, I briefly discuss the analysis of bottom production, which is an important benchmark test, showing that one is indeed able to measure and understand the production of a heavy quark.

II. THE SEARCH FOR THE TOP QUARK

Two different processes contribute to top quark production at a hadron collider:

(i) weak production via $W \to t + \bar{b}$, and
(ii) strong production $p + \bar{p} \to t + \bar{t}$.

The cross-section for weak top production is measured, and hence well known. On the contrary, the cross-section for strong top production is subject to large uncertainties, arising from uncertainties on the structure functions, the Q^2-scale, Λ_{QCD}, and from uncertainties due to contributions of higher, not yet calculated orders in the strong coupling constant. At the Cern Collider with a centre-of-mass energy of 630 GeV, weak top-production dominates over strong top-production at top masses of about 45—75 GeV. This feature is illustrated in Fig. 6.

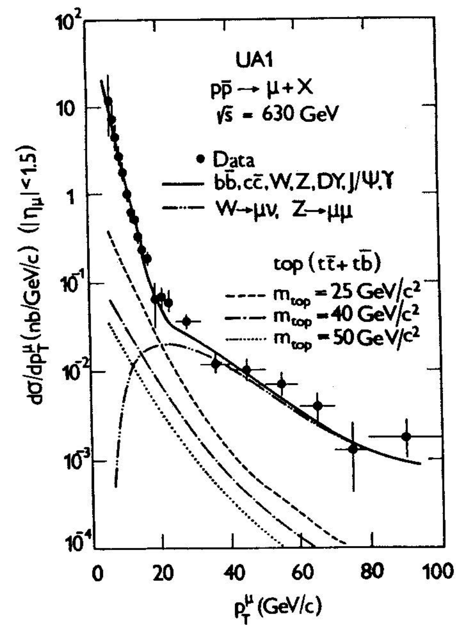

Fig. 1. The inclusive muon momentum spectrum, $d\sigma/dp_T(\mu)$, versus $p_T(\mu)$. The data are compared with Monte Carlo calculations including: $b\bar{b}$, $c\bar{c}$, *W*, *Z*, Drell-Yan, J/Ψ and Y. The top production for three different masses is shown (m_t = 25.40 and 50 GeV). The data have been corrected for decay background and for acceptance, but not muon momentum measurement errors.

With a present-day detector, and in the background conditions which are characteristic for hadron colliders, only semileptonic top decay modes (into electrons or muons; tau's are not feasible) can be triggered on. The UA1-result

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1) Invited talk at Hadron Structure, PIEŠŤANY, Czechoslovakia, 14—18 November 1988

2) Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, VIENNA, Austria

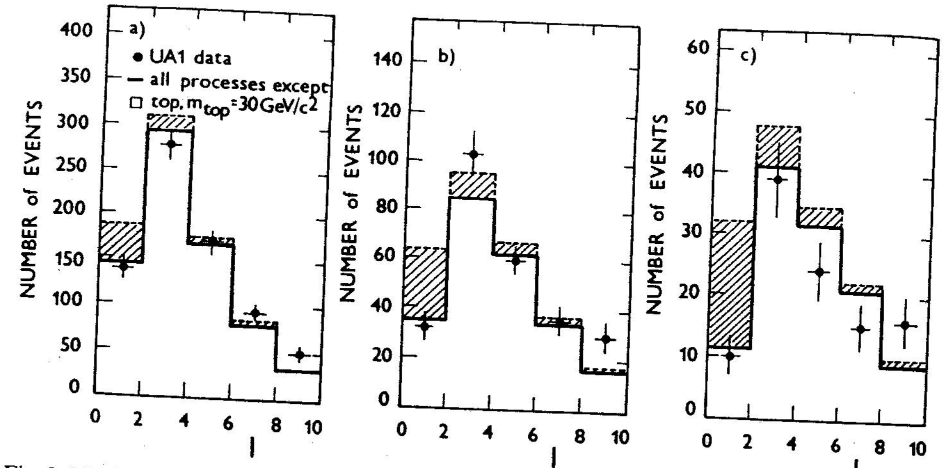

Fig. 2. The isolation variable ($I = [(\Sigma E_T/3)^2 + (\Sigma p_T/2)^2]^{1/2}$ in a cone $\Delta R = 0.7$ around the muon) for three sets of cuts described in the text:

a) $p_T(\mu) > 10$ GeV, E_T(jet − 1) > 12 GeV, $m_T(\mu, \nu) < 40$ GeV, no jet − 2 requirement;
b) $p_T(\mu) > 12$ GeV, E_T(jet − 1) > 15 GeV, $m_T(\mu, \nu) < 40$ GeV, no jet − 2 requirement;
c) $p_T(\mu) > 12$ GeV, E_T(jet − 1) > 15 Gev, $m_T(\mu, \nu) < 40$ GeV, E_T(jet − 2) > 7 GeV.

The solid histogram represents the Monte Carlo calculation for the background processes without top. The hatched area represents the contribution of a 30 GeV mass top quark. The black points with error bars are the UA1 data.

[4] on the inclusive muon cross-section is shown in Fig. 1. The data correspond to an integrated luminosity of 556 nb^{-1}. Top makes only a small contribution to the inclusive muon yield. The muon Spectrum is dominated by bottom below 10—12 GeV, and by *W* and *Z* above 20—25 GeV. Even in the most favourable region, between 12 and 20 GeV, the ratio top/non-top is smaller than 0.10 for top masses of 40 GeV, and decreases very rapidly with an increasing top mass. A further handle is needed to reduce the non-top contributions.

The means to improve the ratio top/non-top are muon isolation and event topology: muons coming from the decay of heavier objects tend, of course, to be better isolated. In the UA1 experiment, isolation is measured with a precision which provides the required reduction factor if used together with further cuts on event topology. This is illustrated in Fig. 2. A cut on the isolation variable I of $I > 2$ rejects about 80% of the events, most of them non-top events. Tightening the cut on $p_T(\mu)$ and selecting events with at least one jet with $E_T > 15$ GeV results in the rejection of 75% of the non-top events (if compared to $p_T(\mu) > 10$ GeV and $E_T > 12$ GeV), at the expense of a loss of 50% of the top events (if $m_t = 30$ GeV; the loss of top events is smaller at higher top masses). Asking for an addtional jet of $E_T > 7$ GeV reduces the number of the non-top events by another factor of about 3. The cut on the transverse mass between the muon and the missing energy reduces the contribution of *W* and *Z* events to a small level (< 1 event).

In Fig. 2, the points with error bars represent the data. The data are described, within the errors, by the sum of non-top processes. If there is any top signal hidden in the data, it cannot be large. The absence of a top signal is converted to an upper limit on the top production cross-section, which may be further converted to a lower limit on m_t.

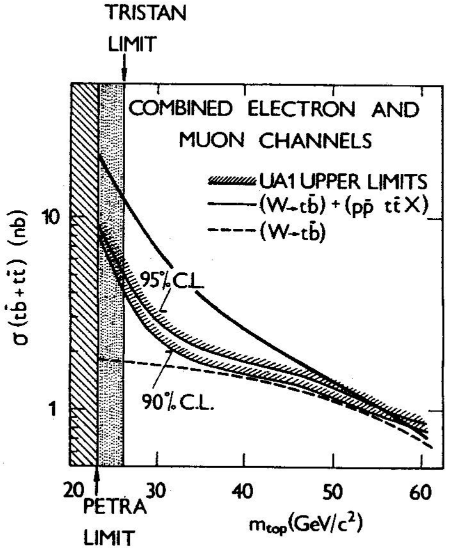

Fig. 3. Confidence level contours in the top quark cross section versus m_t plane from electron and muon information combined. The regions above the curves are excluded at the 90% and 95% confidence levels respectively. The TRISTAN limit ($m_t > 26$ GeV) is indicated ($p\bar{p} \rightarrow t\bar{t}X$) refers to the EUROJET calculation.

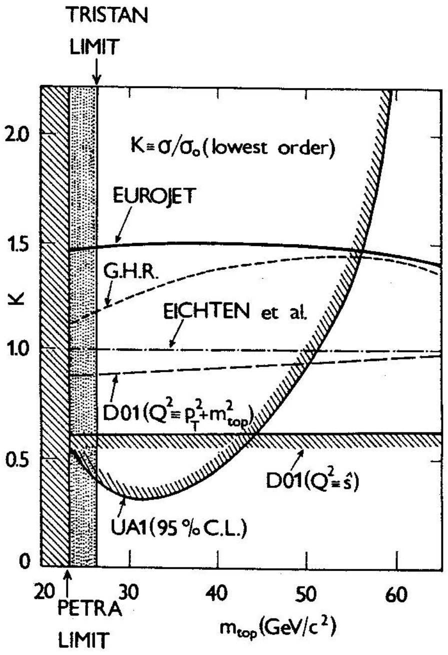

Fig. 4. Sensitivity of the mass limit to the ratio $K = \sigma(t\bar{t})/\sigma_0$, where σ_0 is the lowest order cross-section calculation using EHLQ1 structure functions and $Q^2 = m_t^2 + p_T^2 (K = 1)$. The choice of structure functions (DO1) and Q^2 scale ($Q^2 = \hat{s}$) giving the lowest cross section is shown as shaded curve. The EUROJET calculation corresponds to $K = 1.5$.

A similar procedure is applied to events with electrons. The analysis of events with electrons is a bit less satisfactory, because electron isolation cannot be analysed in detail. For electron identification reasons, a very tight isolation cut has to be applied at the beginning of the event selection. This disadvantage is somewhat compensated by the acceptance of the electron detection system, which is by about a factor of 3 better than that for muons.

The result of a fit to top and non-top contributions in the combined sample of muon and electron events yields limits on the top cross-section as a function of top mass (Fig. 3). The limits improve with increasing mass, because the difference between top and non-top becomes more pronounced as m_t increases. Unfortunately, the limits presented in Fig. 3 do not constrain the well-known weak top production. The sum of both, weak and strong production has to be considered when passing from the cross-section limit to the mass limit. Uncertainties are therefore introduced.

The effect of the uncertainty on the strong top production cross-section is illustrated in Fig. 4. The lowest cross-section is given by DO 1 structure functions and the choise $Q^2 = \hat{s}$. The corresponding mass limit is $m_t > 44$ GeV (at 95% CL).

For the b' quark (the down-like quark of the 4-th generation) the same method as for the top quark was used, except that only strong production was considered to be relevant. The mass limit is $m_{b'} > 32$ GeV (at 95% CL).

After the experimental results have been published [4], some theoretical uncertainties became better understood. The theoretical progress is due to the availibility of a complete $0(\alpha^3)$ QCD calculation. The mass limits on t and b' have hence to be revised [5]: $m_t > 41$ GeV (at 95% CL), and $m_{b'} > 34$ GeV (at 95% CL). The 90% CL limits are by obout 5 GeV higher.

III. TOP SEARCH IN THE NEAR FUTURE

In 1988, the Antiproton Collector (a large acceptance machine which was added in front of the Antiproton Accumulator complex to improve the antiproton accumulation rate, and hence the luminosity in the SPS Collider by about an order of magnitude) became operational. By the end of 1988, an integrated luminosity of about 3 pb^{-1} was delivered by the Cern Collider. Another 5—10 pb^{-1} per year are expected to become available in 1989 and 1990! The upgraded UA2 detector, which is better suited to the top search than the original UA2 setup, operated very well in 1988. About 2 pb^{-1} have already been written to tape. The prospects of the top search with UA2 are illustrated in Fig. 5 [6]. In summary, UA2 is expected to be sensitive to a top quark with a mass of about 65 GeV (with 10 pb^{-1}). The top search in UA2 is done using the electronic decay mode of the top.

Unfortunately, the upgrading of the UA1 detector is not yet completed. With the TMP calorimeter in place (< 1990?), UA1 will be sensitive to top masses of about 70 GeV (with 10 pb^{-1}). A data sample of about 1 pb^{-1} has been written to tape in 1988, which can be used for a further top search in the muon channel.

The Fermilab Collider TEVATRON, operating at a centre-of-mass energy of 1800 GeV was functioning very well in 1988. The CDF Collaboration was able to write to tape a data sample which corresponds to about 2 pb^{-1} The relevance of this achievement is illustrated in Fig. 6 [6]. At top masses above 50 GeV, the top production cross-section is about 10 times higher at the energy available to CDF than at the Cern Collider. So, in principle, CDF has already wiped out both UA2 and UA1. It remains to be seen to which extent this is true, since the top analysis is a complicated enterprise. If CDF performs according to their own expectations, then they already have the data to be sensitive to top with a mass of about 80 GeV. In future, with 10 pb^{-1}, they hope to become sensitive to masses of up to about 150 GeV. In summary, the prospects are good that top will be discovered before the Proceedings in which this article is going to appear will be published.

In the meantime, as long as top is not yet discovered one is allowed to speculate about possible deep reasons, others than simply high top mass, why top has not yet been seen. May be the Higgs sector is more complicated [7] than

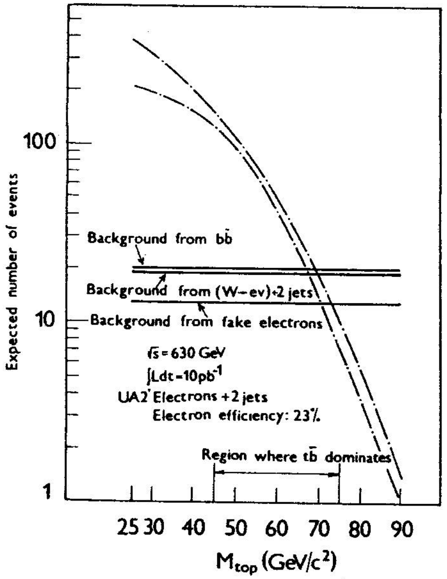

Fig. 5. Expected rates for reconstructed semi-leptonic top decays in UA2 for an integrated luminosity of 10 pb^{-1} as a function m_t. Also shown are the expected background levels from fake electrons and from real electron sources. Acceptances and selection efficiencies are taken into account.

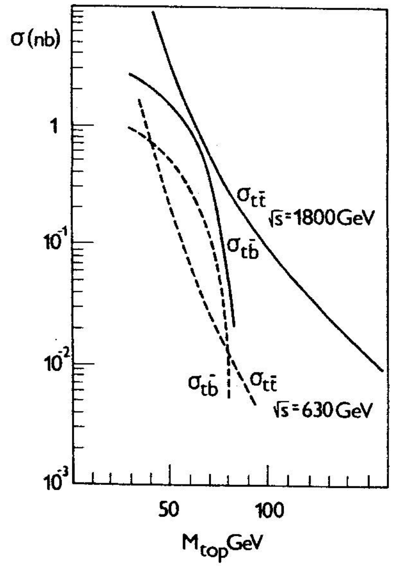

Fig. 6. Top-quark production cross-sections as a function of m_t. The lowest-order cross-sections for weak and strong top production, $\sigma(t\bar{b})$ and $\sigma(t\bar{t})$, are shown for ACOL ($\sqrt{s} = 630$ GeV, broken lines) and TEVATRON ($\sqrt{s} = 1800$ GeV, full lines).

assumed in the minimal Standard Model? If a charged Higgs particle would exist, then top would decay into it (if kinematically allowed) and the charged Higgs would almost exlcusively decay to the heaviest available quarks or leptons, $(c, \bar{s})$ and (τ, ν_τ). Even if m_t were smaller than the mass of the charged Higgs particle, the semileptonic decay of top to electrons or muons would be strongly suppressed. So, maybe top is light after all, just above the recent TRISTAN limit of 27 GeV, and we don't know it, because we are investigating the wrong decay channels.

IV. BOTTOM PRODUCTION

Strong production of bottom (in comparison, weak bottom production is negligible) has been studied by investigating events with non-isolated muons [8]. The muon sample is best suited for this study, since muons can be triggered on at the moderate $p_T(\mu)$ of 2—3 GeV. Muons can further be well identified, irrespective of their isolation properties. Because of the harder fragmentation, muons from the bottom dominate over muons from charm already at a not too high $p_T(\mu)$.

The following different samples with non-isolated muons have been studied:

(1) High-mass dimuons, $M(\mu, \mu) > 6$ GeV; in this case, most of the muons come from 1st-generation decays of both b and $\bar{b}$.

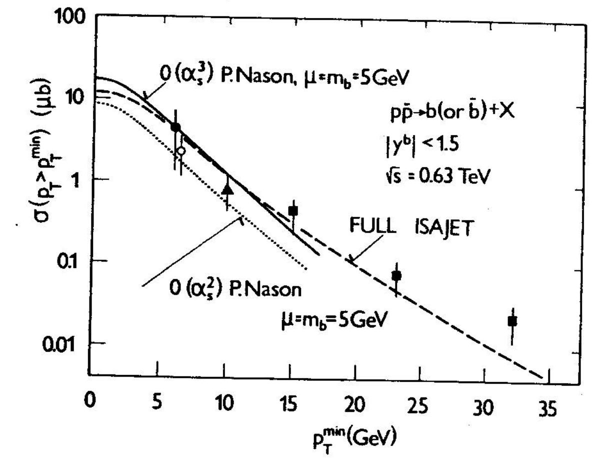

Fig. 7. The inclusive bottom production cross-section in proton-antiproton collisions at $\sqrt{s} = 0.63$ GeV for $p_T(b) > p_T^{min}$ and $|y(b)| < 1.5$ as a function of p_T^{min}. The six experimental points come from the independent measurements discussed in the text: $J/\Psi \to \mu^+\mu^-$ (solid circle), high-mass dimuons (open circle), low-mass dimuons (triangle), inclusive muon sample (open squares). The curves represent the absolutely normalized QCD calculations discussed in the text.

(2) Low-mass dimuons, $M(\mu, \mu)$ is about 2 GeV; one of the muons comes from the 1st, and the other from the 2nd-generation decay of the same b quark.

(3) $b \to J/\Psi$, followed by $J/\Psi \to \mu^+\mu^-$.

(4) Single muon sample (one of the background reactions in the top search), with 10 GeV $< p_T(\mu) <$ 25 GeV.

Due to different cuts in the trigger and in the selection procedure, each of the reactions (1) to (4) corresponds to a different p_T of the parent bottom quark. The inclusive bottom cross-section obtained in the analysis [8] is presented in Fig. 7. Sample (4) has been subdivided into 3 bins. Three absolutely normalized QCD calculations are shown for comparison with the data: The $0(\alpha^2)$ and $0(\alpha^3)$ calculations of Nason [9], and the full ISAJET calculation including the processes of 'flavour excitation', 'gluon splitting' and 'flavour creation'. For p_T values large compared to the mass of the bottom quark, the $0(\alpha^3)$ calculation is unreliable. For this reason the curve of Nason is available only up to 15 GeV; in this region it agrees well with the data. At higher p_T, an extrapolation of the $0(\alpha^3)$ curve seems to underestimate the data. The total cross-section for the production of $(b, \bar{b})$ pairs, integrated down to $p_T = 0$, is estimated by fitting the normalization of the $0(\alpha^3)$ to the data shown in Fig. 7, by extrapolating to all rapidity, and by dividing by two:

$$\sigma(p + \bar{p} \to b + \bar{b} + X) = 10.2 \pm 3.3\ \mu\text{b}.$$

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ИЗУЧЕНИЕ ТЯЖЕЛЫХ КВАРКОВ НА АНТИПРОТОН-ПРОТОННОМ ЛПЯАКДЕРЕ ЦЕРМа

В работе приводится обзор сегодняшних знаний о нижнем и верхнем, как и возможной 4-той генерации кварков, полученных на колайдере ЦЕРНа. Обсуждаются возможные открытия в 1989 и в последующих годах.