ASYMMETRIC COLLIDER

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1. INTRODUCTION

The study of *CP* violation in beauty decay is one of the key challenges facing high energy physics [1]. Much work [2] has not yielded a definitive answer how this study might best be performed. However, one clear conclusion is that new accelerator facilities are needed. Proposals include experiments at asymmetric electron-position colliders [3] and in fixed-target and collider modes at LHC [4] and SSC [5]. Fixed-target and collider experiments at existing accelerators, while they might succeed in a first observation of the effect, will not be adequate to study it thoroughly.

Giomataris [6] has emphasized the potential of a new approach to the study of beauty *CP* violation: the asymmetric proton collider. Such a collider might be realized by the construction of a small storage ring intersecting an existing or soon-to-exist large synchrotron, or by arranging collisions between a large synchrotron and its injector. An experiment at such a collider can combine the advantages of fixed-target-like spectrometer geometry, facilitating triggering, particle identification and the instrumentation of a large acceptance, while the increased $\sqrt{s}$ can provide a factor > 100 increase in beauty-production cross section compared to Tevatron or HERA fixed-target. Beams crossing at a non-zero angle can provide a small interaction region, permitting a first-level decay-vertex trigger to be implemented [7]. To achieve large $\sqrt{s}$ with a large Lorentz boost and high luminosity, the most favorable venue is the high-energy booster (HEB) at the SSC Laboratory, though the CERN SPS and Fermilab Tevatron are also worth considering.

We next comment on these issues in somewhat more detail:

1. The cross section for beauty production in hadron collisions is a rapidly increasing function of energy at currently available energies [8]. Thus a modest increase in $\sqrt{s}$ can provide a large increase in beauty production rate.

2. A Lorentz-boost γ confines the beauty decay products, distributed ≈ isotropically in the center of mass, to a cone of typical half-angle $\tan^{-1}(1/\gamma)$. Thus less detector area is needed with boosted events, and a spectrometer of given cost can have higher beauty detection probability. An additional effect is that much of the increase in beauty cross section at very high $\sqrt{s}$ consists of events produced in the extreme foreward or backward direction , which typically go down the beam pipe undetected. These are exemplified by comparing the (expensive) CDF detector, with beauty geometrical acceptance < 10% for typical decay modes, with the (more modest) fixed-target detectors of Fermilab Proposal 865 [9] and the HERA-B proposal [10], whose acceptances for typical decay modes are > 50%.

3. At the values of $\sqrt{s}$ (~a few hundred GeV) we are considering, beauty events are distinguished by substantially higher transverse momenta than are typical of "minimum-bias" background events, and this distinction can be used in the trigger to reject the background. At ultra-high energy (e.g. Tevatron or SSC collider), the mass of the b quark becomes negligible with respect to the available center-of-mass energy, so that beauty production becomes kinematically similar to the background.

4. The ability to trigger on the beauty decay vertex is crucial to carrying out a sensitive study of beauty decay in a wide variety of modes. Thus (for example) CDF intends to implement a fast vertex trigger for Tevatron Run II, and the optical impact-parameter trigger features prominently in the LHC fixed-target "GAJET" proposal. Other triggering schemes provide inadequate sensitivity, for example the high-p_t dilepton triggers currently in use by CDF have efficiency < 1% for the ~ 1% of beauty decays to J/ψ, and the high-p_t single-muon trigger used by the Fermilab fixed-target experiment E771 is < 50% efficient for the ~ 10% of beauty decays to muons. Tests of the optical impact parameter trigger are in progress at CERN; it appears likely that background rejection factors ~ 10-100 can be achieved with beauty efficiency > 50%, largely independent of decay mode.

5. Hadron identification is key in a beauty experiment, for example it makes possible kaon-tagging of the initial beauty quantum number [10], and it improves the signal/background ratio for the kaon-rich final states of the copious beauty to charm decay cascade. The higher momenta of Lorentz-boosted beauty decay products and the fixed target-like spectrometer layout facilitate effective hadron identification using threshold or ring-imaging gas Cherenkov counters.

We estimate [6] that given the good acceptance and trigger efficiency possible in an asymmetric-collider experiment, ~ 10^{10} produced beauty events per year should permit a detailed study of beauty *CP* violation, as well as other topics of interest such as B_s mixing and flavor-changing neutral-current decays [9, 11]. This calls for luminosity in the range ~ 10^{32} - 10^{33} cm^{-2} sec^{-1}; the exact value needed depends on $\sqrt{s}$ and the still imperfectly known beauty cross section, as well as how much running time is made available per year. We have begun studies to understand the limits to luminosity in asymmetric configurations with various crossing angles.

2. SCALING LAWS FOR THE ASYMMETRIC COLLIDER USING THE TEVATRON

One option explored at this workshop was the possibility of an asymmetric collider using the Tevatron and a new machine whose energy and size are to be specified.

The following conclusions were reached in these discussions:

1. space charge forces are the dominant limit to intensity in the low energy ring; these may be mitigated, to some degree, by the use of flat beams;

2. beam-beam forces, and the associated tune shift in the high energy beam, are the primary limits to intensity (and emittance) in the high energy machine; an assumption was made to limit the fraction of the total beam-beam tune shift due to the new interaction region to approximately one third of the now acceptable level; this will reduce the detector luminosities by about 1/3;

3. geometric constraints most likely will preclude the use of common quadrupoles for the low energy and high energy rings in the interaction region; thus large-angle, or even 90° crossing is preferred.

Based on these considerations, a simple scaling law for the asymmetric collider could be obtained. In the low energy machine, the acceptable space charge tune shift is of order unity, and in terms of machine parameters is given by

$$\Delta\nu_{sc}=\frac{\tilde{N}_L r_o (1-\beta_L^2)\beta_{yL} g_L}{4\pi\beta_L\gamma_L(1+a_L)\sigma_{yL}^2}$$

where g_L is the fraction of particles intersecting the high energy ring, a_L is the ratio of the horizontal to vertical beam sizes, r_o is the classical proton radius, β_{yL} is the vertical beta function, N_L is the number of particles in the ring, s_{yL} is the vertical beam size and γ_L and β_L are the usual relativistic factors. For a flat bunched beam in the high energy ring intersecting a DC beam in the low energy ring at right angles, the following approximate expression for the luminosity can be given

$$L=\frac{N_H N_L g_L f_o}{4\pi\sigma_{yL}\sigma_{yH}}$$

The beam sizes in the respective rings are forced to be equal and are given by

$$\sigma_{yL}=\sqrt{\frac{\varepsilon_{NL}}{6\pi\gamma_L}}=\sigma_{yH}$$

where a_L and a_H are the aspect ratios of the respective beams. Using the space charge limit above, the maximum luminosity can be expressed in the following form

$$L_{sc}<\frac{\beta_L\gamma_L^{5/2}\varepsilon_L^{1/2}N_H f_o a_H(1+a_L)}{2\sqrt{6}\pi^{3/2}R_L r_o\beta_{yL}^{1/2}}\Sigma$$

where Σ is the maximum allowable tune shift, taken here to be 0.1. Now it is further noted that there is a maximum allowable field strength in present-day magnets at about 6T with a minimum bend radius of about 8 m. This means that R_L is actually a function of energy above about 14 GeV. Anticipating this limit, the final form of the space charge limit is in the following form, using Tevatron parameters:

$$L_{sc}<6.5\times10^{29}\,\frac{\gamma_L^{3/2}a_H(1+a_L)}{\beta_{yL}^{1/2}}\ \text{cm}^{-2}\text{sec}^{-1}$$

We now invoke the limit due to the beam-beam forces exerted by the low energy ring on the high energy ring, given by

$$\Delta\nu_{BB}=\frac{\tilde{N}_L r_o (1+\beta_L^2)\beta_{yL} g_L}{4\pi\beta_L\gamma_L(1+a_L)\sigma_{yL}^2}$$

In a similar fashion we have the limit due to the beam-beam tune shift as

$$L_{B\text{-}B}<2.0\times10^{29}\,\frac{\gamma_L(1+a_L)}{\beta_{yL}}\ \text{cm}^{-2}\text{sec}^{-1}$$

In the above we have made the assumption that the maximum allowable tune shift due to beam-beam effects is about one-third of the present allowable tune shift in the Collider. This causes a reduction of the Collider luminosity of about 1/3. If we now further assume that the minimum beta function in the Tevatron is on the order of a few meters with an emittance of 20π (present conditions, see below), then the dominant limit on the luminosity becomes the beam-beam limit.

The results are plotted in Fig. 1 against the necessary luminosity as governed by the bb cross-section. This shows that a possible solution can be found at a value of $\gamma_L = 100$. If an aspect ratio of 10:1 can be achieved in the high energy ring in the interaction region, then $\gamma_L = 100$ with $\beta_L = 4$ m and $\beta_H = 2$ m. Such a situation is viable provided a new low-β region can be installed.

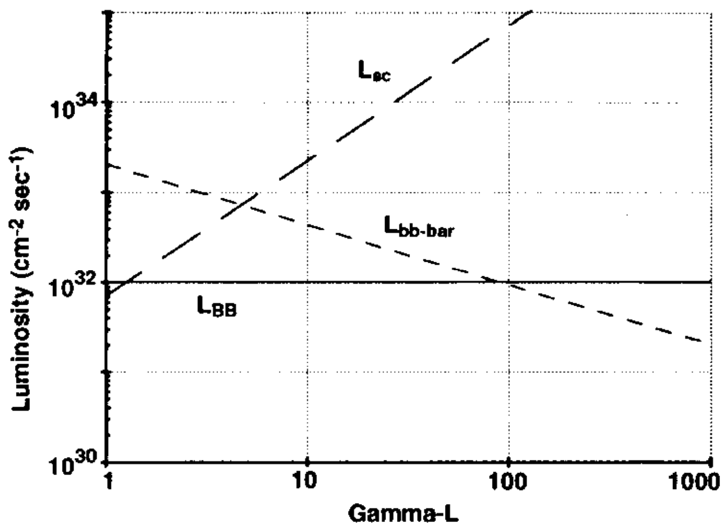

Fig. 1 Luminosity limits due to space charge and beam-beam forces plotted versus the required luminosity for b-b-bar events. Beam-beam limits dominate requiring $g_L > 100$ for sufficient luminosity.

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