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A $\mu^+\mu^-$ COLLIDER USING BENT CRYSTALS AND A NEUTRON SPALLATION SOURCE INJECTOR*

UCLA-CAA-0132-8/96

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We briefly describe some of the scientific goals of a $\mu^+\mu^-$ collider and the possible development of a very compact collider using bent crystals. We then show that low-energy $\mu^\pm$ beams cooled by fricional cooling and produced at a powerful spallation source could make this scheme feasible even with the current tight budgets.

1 Physics Goals of $\mu^+\mu^-$ Colliders

Over the past three years, several workshops have been organized to study the physics potential[1-5] and machine design of a $\mu^+\mu^-$ collider. Two energy ranges have been identified, 2 × 2 TeV and 250 × 250 GeV (studied first by the author[3,6]).

At the Napa workshop, the possibility of developing a $\mu^+\mu^-$ collider in the range of luminosity of 10^{31} cm^{-2} s^{-1} was considered and appears feasible.[2,3] However, higher luminosity will be required for the Higgs sweep. It is less certain that the high-energy resolution required for the Higgs sweep can be obtained.[6]

From the presentations given at the conferences in Sausalito and Napa[4] and more recently at the Fairmont Hotel conference,[5] it seems that luminosity of perhaps 10^{33} cm^{-2} s^{-1} is feasible, if we combine polarized $\mu^\pm$ beams and, thus, we will have a most powerful Higgs factory and scalar collider. There are strong physics arguments for a low-energy $\mu^+\mu^-$ collider.[4,7] The arguments for a multi-TeV $\mu^+\mu^-$ collider are much more speculative.[7] See Fig. 1 for the physics threshold for a $\mu\mu$ collider.

The strongest argument for the low-energy 250 × 250-GeV collider comes from the growing evidence that the Higgs should exist in this low-mass range of 100 – 190 GeV.

The most interesting question in particle physics now is associated with the origin of mass. It is generally assumed that the exchange of fundamental scalar particles, called the "scalar sector" is somehow responsible for this. For supersymmetry modes, this scalar sector is even more complex and interesting (see Table 1).[3,5,8]

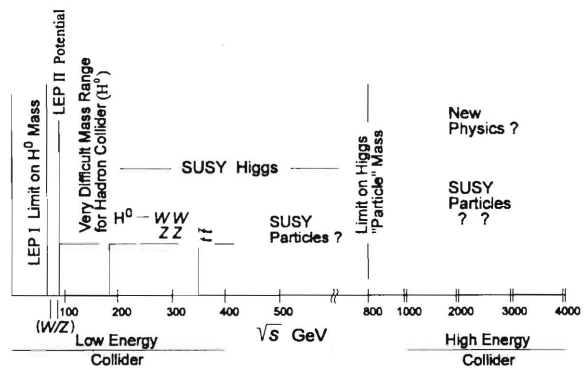

Figure 1: Physics Threshold for a $\mu\mu$ Collider.

In this section, we highlight one of the most interesting goals of a $\mu^+\mu^-$ collider: the discovery of a Higgs boson in the mass range beyond that to be covered by LEP I & II (~80–90 GeV) and the natural range of the supercolliders.

There are several ways to determine the approximate mass of the Higgs boson in the future.[6] Suppose it is expected to be at a mass of 135 ± 2 GeV, the energy spread of a $\mu^+\mu^-$ collider can be matched to the expected width (see Fig. 2). An energy scan could yield a strong signal to background especially with polarized $\mu^+\mu^-$ in the scalar configuration.[6,7] Once the Higgs is found, the following could be carried out:

1. Measurement of width, to separate standard model Higgs from SUSY or other Higgs models,[7]
2. Measurement of the branching fractions, the rare decay will involve loop effects that can sample very high energies.

Polarization will play an essential role for any $\mu^+\mu^-$ collider![7,8]

The status of the *t* quark study from FNAL for the CDF detector was reviewed by D. Amidei at the

*Prepared for the Proceedings of the Symposium on the Savannah River Accelerator Project and Complementary Spallation Neutron Sources (Univ. of South Carolina, Columbia, May 1996).

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Table 1: The Scalor Sector.

With a high-mass t quark, precision LEP/SLD data and the theorists' dreams of a SUSY world, the scalar (pseudo-scalar sector) is possibly very complex and may require several types of colliders.[7] Consider:

- If the low-mass Higgs has $m > 130$ GeV, MSSM is not allowed.
- If $m > 200$ GeV, there are constraints from the requirement that perturbation theory be useful up to very high energy and from the stability of the vacuum.
- If $m < 130$ GeV, MSSM is possibly ok, but we may expect other particles (H, A), and the width of the low mass Higgs may change.
- The scalar sector may be extremely complex, requiring pp (LHC) and $\mu^+\mu^-$ colliders (and possibly NLC and $\gamma\gamma$ colliders).
- In high energy collisions, vector states are allowed unless a special method is used. Consider $\mu^+\mu^-$ colliders with polarized $\mu^\pm$:

$\mu^+\mu^-$ → (100–500) GeV – scalars (H, A, ...) — W^+W^-

$\mu^+\mu^-$ → $\geq 2 +$ TeV — Z^0Z^0 production in scalars

This cannot be done for pp or e^+e^- colliders.

- A $\mu^+\mu^-$ collider is complimentary to the LHC/CMS detector.

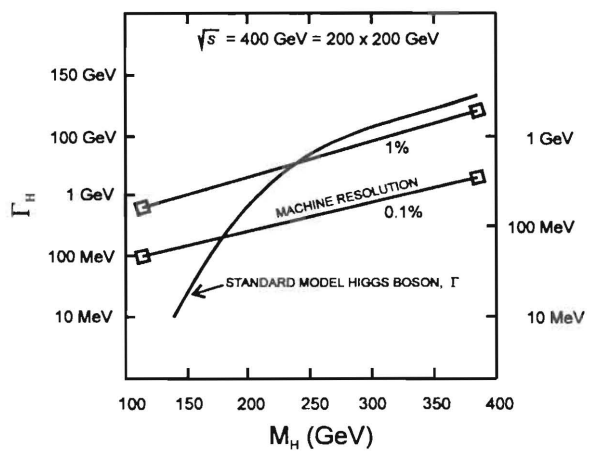

Figure 2: Higgs search at a $\mu^+\mu^-$ Collider (Required Machine Resolution and the Expected Higgs Width).

Fairmont meeting.[9] In Fig. 3, we show the Feynman diagrams for the production of $t\bar{t}$ for both e^+e^- and $\mu^+\mu^-$ collisions.[8] Because of the larger mass of the μ compared to the e, the diagram with a scalar intermed iate state can be important (see B in Fig. 3). If we fully polarize the $\mu^+\mu^-$ system to give a net zero scalar state, we believe the scalar sector will be enhanced to the point that a measurable asymmetry will be generated. Thus, one could search for evidence of scalar particles far from the central mass. This is a unique feature of polarized $\mu^+\mu^-$ colliders.[8] The detector design will play a crucial role in such studies.[10]

2 A Collider Using Bent Crystals

For our model calculation, we consider two counter propagating 250 × 250-GeV $\mu^\pm$ beams brought to collision inside the ultra-strong focusing environment of a crystal channel. Both muon species are "confined" to the corresponding crystal channels inside a low-Z binary crystal, *e.g.*, LiF.

The luminosity of the collider can be estimated in the following way,[11] with the luminosity per single channel given by

$$L_c = \frac{\gamma\, n_+ n_- f}{4\pi\beta^* \epsilon_N^{\min}} \quad , \qquad (1)$$

where n_+ and n_- are numbers of muons (both species) present in the channel. Here we assume $n_+ \sim n_- \sim 10^5$,

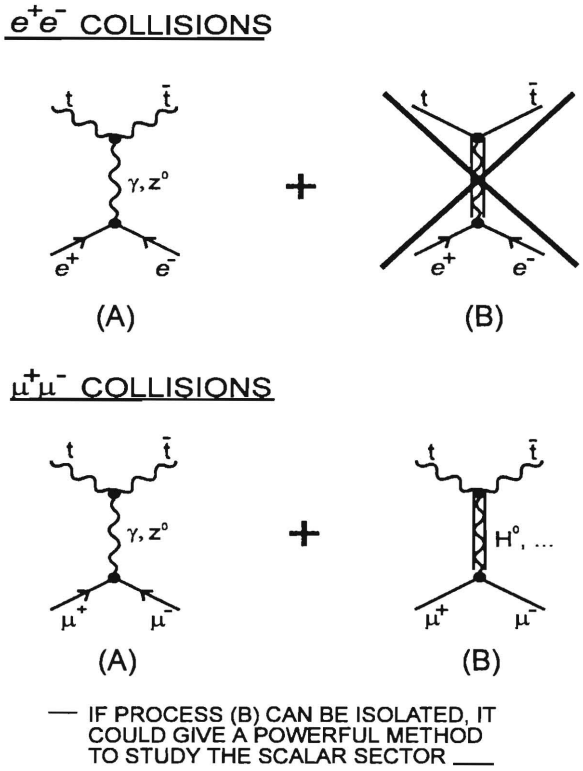

Figure 3: $t\bar{t}$ Production at $\mu^+\mu^-$ Colliders.

$\beta^* = 6 \times 10^{-6}$m is the equivalent beta star inside a binary crystal, $\epsilon_N^{min} = 2.5 \times 10^{-9}$ m rad is the normalized transverse emittance (achieved by fast-ionization crystal cooling), and f denotes the revolution frequency (we assume $f \sim 3 \times 10^6$ s^{-1}).

In order to take advantage of the quantum confinement[12] inside a crystal channel, the beam size, σ, has to be no greater than the crystal channel width (~ 10 Å). As one can see from the following formula,

$$\sigma = \sqrt{\frac{\epsilon_N^{min}\beta^*}{\gamma}} \quad , \qquad (2)$$

the $\mu^\pm$ beams with emittances of $\epsilon_N^{min} = 2.5 \times 10^{-9}$ m rad can easily fit inside a crystal channel, $\sigma \sim 10^{-9}$ m. Applying the above numerical values to Eq. 1 yields the single-channel luminosity of $L_c \sim 10^{29}$ cm^{-2} s^{-1}.

To estimate the net luminosity of a whole crystal, we need to know how many crystal channels are "occupied" (we conservatively assume $N_c \sim 10^3$). The total luminosity is then given by

$$L = N_c L_c \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \quad . \qquad (3)$$

Here we employ previously discussed properties of the planar channeling of high energy muons in silicon to design components of a storage ring. Particularly, we are interested in a section of bent crystal followed by two straight pieces providing alternating horizontal/vertical focusing. A basic guiding cell is depicted schematically in Fig. 4. It can be noticed that the induced configuration of guiding fields in this element is equivalent to a powerful alternating-gradient achromat.

Relativistic muons channeling through an Si crystal are confined between two neighboring atomic planes where they experience strong focusing electrostatic crystal potential in the direction perpendicular to these planes, while there is virtually no confinement in the direction parallel to the planes (no focusing or defocusing). The crystal focusing gradient, $k = 1/\beta$, which is equivalent to the magnetic quadrupole strength, k_1 (the magnetic gradient) is

$$k_1 = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} \quad , \qquad (4)$$

which is given by the following formula

$$k = \frac{\phi}{E_\mu} \quad , \qquad (5)$$

where E_μ is the total muon energy and $\phi = 6 \times 10^{12}$ GeV m^{-2} is a material constant, related to the curvature of the potential well.[13] Assuming 250-GeV muons, the crystal focusing gradient, k, yields an enormous value of 18 m^{-2}, exceeding conventional quadrupole strength by three or four orders of magnitude.

As discussed previously, the crystal can be bent slightly so that channeling muons follow the curvature of the guiding field, which results in the bending of muon trajectories similar to the effect of bending a magnetic field. Projecting experimental results for proton channeling in a bent silicon crystal, one can assume that 250-GeV muons channeling through an 8-cm-long crystal should follow (without significant dechanneling effects) a bend of $\theta = 2\pi \times 10^{-2}$ rad (compared with the critical bending angle, $\theta_T = 2 \times 10^{-2}$ rad). The lattice design presented here is based on these two numbers, k and θ.

Figure 4 illustrates a functional bending-focusing cell, where alternating sections of the horizontal and vertical continuously focusing channels are combined with sections of horizontally bent Si crystals. The following sequence of crystal elements completes the

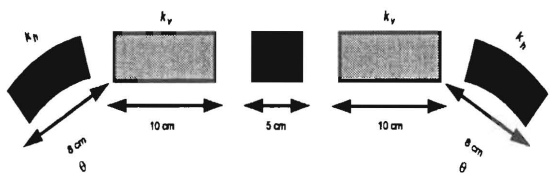

Figure 4: Bending-Focusing Cell ($k_h = k_v = 18$ m^{-2}; $\theta = 2\pi \times 10^{-2}$ rad).

proposed elementary cell: a horizontally focusing bent crystal (8-cm long) - a short drift space (1-cm long) - a vertically focusing straight crystal (10-cm long) - 1 short (5-cm long) horizontally focusing straight crystal - another vertically focusing straight crystal (10-cm long) - a short drift space (1-cm long) - another horizontally focusing bent crystal (8-cm long) and finally - a short drift space (1-cm long). At 250 GeV, one could close the entire collider ring using 50 of the above $F_h F_v F_h OO F_h F_v F_h O$ cells. This ultra-compact collider ring would have a circumference of 22 meters!

For a sequence of the above described cells, one can find periodic betatron trajectories in both the horizontal and vertical planes - the betatron phase stability is provided by the proposed lattice configuration (alternating horizontal/vertical focusing). A crystal channel provides ultra-strong electrostatic focusing gradient in [110] direction with practically no confinement or defocusing in the plane perpendicular to [110] direction. This fact guarantees both local and global decoupling[14] of the horizontal and vertical betatron motions for the proposed collider lattice.

Starting with an initially "cool" muon beam (coming from a conventional hadronic source, $p + A \rightarrow \pi \rightarrow \mu$), the longitudinal phase-space for low-energy $\mu^{\pm}$ beams can be further reduced (*e.g.*, by utilizing frictional cooling[15,16]) before the final transverse cooling is applied. Our model calculation, presented here, shows that emittance can be decreased to less than $\epsilon_N = 10^{-8}$ m rad by passing the muon beam through a cascade of many cooling modules. Experimental demonstration of fast- ionizing crystal cooling is under way (*e.g.*, E763, the muon cooling and acceleration experiment at TRIUMF[17]). Dominant heating process (due to multiple scattering on the electron gas inside a crystal channel) has also been taken into account. The derived transverse-emittance "cooling equation"[18] shows that the minimum achievable emittance (equilibrium cooling limit) is of the order of $\epsilon_N^{\min} = 2.5 \times 10^{-9}$ m rad, while the characteristic transverse-emittance damping length is about 62.5 m.

We have outlined here a conceptual scheme for a 250 × 250-GeV muon-collider complex. It involves fast muon cooling via ionization energy loss in a novel bent-crystal cooling ring, as well as quantum confinement[12] of colliding $\mu^{\pm}$ beams inside a low-Z binary crystal. A binary crystal provides a unique configuration of "potential wells," which allows for accommodation of both $\mu^{\pm}$ species in a crystal. Thermal non-equilibrium or metastable equilibrium states induced by the lattice vibrations (finite temperature) could be utilized as a mixing mechanism,[19] which may bring both muon species to a collision in a crystal channel.

3 Use of an Intermediate Energy Proton Driver for the $\mu^{\pm}$ Source

At the Fairmont meeting, several talks were devoted to the development of intermediate energy proton drivers.[5] It is believed that such drivers could be used for a $\mu^{\pm}$ source, provided the designers plan for this. The proton source discussed at this meeting could also be used in this mode, in our opinion. The development of a $\mu^+\mu^-$ collider could be of great importance to frontier elementary particle physics in this country.

Acknowledgement

Portions of this paper were adapted from a paper co-authored by A. Bogacz, and I wish to thank him for his helpful work on this paper as well as others on this subject.

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