Key points of the physical program for some new colliders

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Abstract

I discuss two different themes:
1. Complete Higgs discovery at different colliders.
2. Physical program for future μp collider.

1 Higgs boson at different colliders

1.1 Main problems for the Higgs boson discovery

The main goal for future large colliders is the discovery of the Higgs boson (HB). In the Standard Model ($\mathcal{SM}$) HB is responsible for the observed breaking of the basic $SU(2)\times U(1)$ symmetry; the fundamental particles acquire masses through the interaction with scalar Higgs field. Until discovery of the Higgs boson we cannot believe that our world is governed by the $\mathcal{SM}$.

In the *simplest variant of the* $\mathcal{SM}$ — $\mathcal{SSM}$ — the Higgs field, before symmetry breaking, is weak isodoublet. In our world, after the symmetry breaking, the Higgs sector contains one selfinteracting scalar and the only free parameter of theory is its mass M_H . The HB width Γ_{tot} is determined by its mass entirely. This HB should be lighter than 800 GeV, because HB with larger mass disappear in the background. (At $M_H > 800$ GeV we deal with strong HB selfinteraction.)

Construction of the $\mathcal{SM}$ admits different variants of Higgs sector. Before symmetry breaking, Higgs fields can be several (weak) isotopical doublets, triplets etc. (in the $\mathcal{MSSM}$ — 2 doublets.) For instance, in 2–doublet model, after symmetry breaking, the physical Higgs sector contains two neutral scalars, one neutral pseudoscalar ($\mathcal{CP}$ odd) (in some variants with scalar — pseudoscalar mixing) and two charged Higgses. There is large variety in possible couplings and sets of physical fields here. (These variants give no new opportunities for HB discovery, except an additional window for very light Higgs, with the mass above 3 GeV, at some extreme values of parameters.)

In subsequent discussion we speak about HB in the $\mathcal{SSM}$. Some cloud of parameters of more complex models (two doublets, the $\mathcal{MSSM}$,...) is covered with the same efforts.

The real discovery of HB needs a solution of the series of problems (or a large part of them). They are discussed in sec. 1.4.

1.2 Colliders

Let us describe briefly some features of high energy colliders which are under discussion now in respect to HB discovery. We will speak below about the beam energy E, its energy spread $\Delta E=\sqrt{<E^2>-<E>^2}$, the mean degree of the longitudinal (circular) polarization λ and the luminosity $\mathcal{L}$.

The **Hadron colliders** (the Tevatron and LHC after upgrad) are well known.

Next Linear Colliders in e^+e^- mode with the beam energy $E_e = 0.25 \to 1$ TeV are discussed in details in refs. [4].

These linear colliders will be complexes having e^+e^- mode and **Photon Colliders (γe and $\gamma\gamma$)** modes — **PLC** — with typical parameters listed in tables of ref. [4, 5].

The Muon Collider ($\mu^+\mu^-$) — MC — and its first stage — **First Muon Collider (FMC)** are under wide discussion now with parameters given in Table from ref. [8], [9]:

	FMC	*MC*	*PLC*
Beam energy E	*50 GeV*	$0.25 \to 2$ *TeV*	$E_\gamma \approx 0.8 E_e$
Energy spread ΔE	*6 MeV*	$\geq 5 \div 10$ *MeV*	$(0.05 \div 0.07) E_\gamma$
Annual luminosity $\mathcal{L}$, fb^{-1}	*1* fb^{-1}	$100 \to 1000$	$10 \div 30$
Beam polarization λ	$\sim 60\%$ *[9]*		$\sim 95\%$ *[5]*

The sign of photon helicity at PLC can be easily changed [5]. One can transform circular polarization of the PLC into linear one [10].

Relatively easily one can obtain the luminosity of the PLC $\mathcal{L}_{\gamma\gamma}$ about $(0.2 \div 0.3)\mathcal{L}_{ee}$ — the luminosity of the initial e^+e^- collider. The numbers in the table [4] correspond to the discussed annual luminosity $\mathcal{L}_{ee} = (30 \div 100)$ fb^{-1}. With the discussed enhancement of TESLA luminosity in e^+e^- mode by about one order, the magnitude of $\mathcal{L}_{\gamma\gamma}$ will be higher by the same factor. With special efforts at the stage of damping rings or earlie the magnitude of $\mathcal{L}_{\gamma\gamma}$ can be even larger than the basic e^+e^- luminosity.

One can have also $\mathcal{L}_n \approx 3\mathcal{L}_b$ in the *nonmonochromatic* variant of PLC with $\Delta E \sim E_\gamma$ One can prepare *supermonochromatic* variant with $E_\gamma \approx 0.95 E_e$ and $< \Delta E_\gamma > \approx 0.01 E_\gamma$ but with $\mathcal{L}_s \sim 0.1 \mathcal{L}_b$.

One can change direction of spin in MC relatively easily [9]. The degree of polarization here can be enhanced (and energy spread will be reduced simultaneously) with reduction of luminosity.

1.3 Dominant decay channels and discovery reactions

The potential of large colliders for the discovery of the Higgs boson was studied in many papers. It is reviewed in refs. [2, 3, 4, 6] — in details for Hadron colliders, e^+e^- Linear Colliders and FMC and in some points for PLC. It was shown that most of properties of HB will be obtained by combination of results from different experiments.

The results obtained at some single collider are preferable for the discussed problem, since an influence of systematical inaccuracies here can be reduced much more strongly. In this respect, it is useful to compare the potential of different colliders for these problems.

The strategy of HB discovery depends on its mass.

Theoretical limitations. In the $\mathcal{SSM}$ with t–quark mass $M_t = 175$ GeV the vacuum stability needs $M_H > 105$ GeV. **There are less strong reasons in favor of mass interval** $130 - 180$ **GeV.** The most probable estimate from the high–precision electroweak data gives $73 < M_H < 310$ GeV [1]. In the $\mathcal{MSSM}$ $M_H < 130$ GeV.

The interval $M_H \leq 95$ GeV will be covered at LEP2 in nearest future. The upgraded Tevatron + LEP2 promise to cover mass interval up to $M_H = 430$ GeV.

The total HB width. This width is less than 10 MeV at $M_H < 140$ GeV, it is larger than 10 GeV at $M_H > 310$ GeV, $\Gamma_H / M_H > 1/4$ at $M_H > 700$ GeV; Γ_H exceed reasonable energy resolution of almost any detector at $M_H > 350 \div 400$ GeV.

Decay channels. For $M_H < 135$ GeV the main decay channel is $H \to b\bar{b}$. It is expected to find such HB at the Tevatron or e^+e^- linear collider via the $b\bar{b}$ (mainly) or $\gamma\gamma$ decay.

If $M_H > 2M_Z$, HB can be discovered at all colliders via the sizable decay mode $H \to ZZ$. A background to this decay mode is rather small.

The mass range $M_H = 140 - 190$ GeV is the most difficult one for HB discovery. In this mass range the decay mode $H \to W^+W^-$ with real or virtual W's ($W^* \to q\bar{q}, e\bar{\nu}, ...$) is dominant, branching ratios of other decay modes become small, and their use for HB discovery is difficult. The use of the $H \to W^+W^-$ decay at e^+e^- collider is also difficult due to a strong nonresonant W^+W^- background. HB with the mass $M_H = 140 - 190$ GeV can be discovered at the PLC via the $H \to W^+W^-$ decay mode [7] with high efficiency.

The pp, $p\bar{p}$, e^+e^- , γe colliders provide opportunity to study the **nonresonant Higgs production**. List of reactions and decays considered is in the table below. (The missing mass method in the reaction $e^+e^- \to HZ$ is noted here as MM.)

M_H GeV	$\bar{p}p$, pp		e^+e^-	
	production	decay	production	decay
$95-130$	$WH+...$, $ZH+...$ $t\bar{t}H+...$, $H+...$	$b\bar{b}$, $\gamma\gamma$	ZH	MM, $b\bar{b}$
$130-155$	$H+...$, $WH...$, $t\bar{t}H+...$	WW^*, ZZ^*, $\gamma\gamma\,(?)$	ZH, $H\nu\bar{\nu}$	MM, bb, WW^*
$155-180$	$H+...$	WW, ZZ^*	ZH, $H\nu\bar{\nu}$	MM, WW, ZZ^*
$180-210$	$H+...$	WW, ZZ	ZH, $H\nu\bar{\nu}$	MM, ZZ, WW
>210	$H+...$	ZZ	$H\nu\bar{\nu}$	ZZ, WW

At the FMC and PLC we deal with **resonant Higgs production** — reactions $\mu^+\mu^- \to H$ or $\gamma\gamma \to H$. The table shows observable decay channels here. (The brackets [ ] shows decay modes that seem observable but they have not been studied study yet.)

M_H GeV	$\gamma\gamma$ collider	$\mu^+\mu^-$ collider
$95-120$	$b\bar{b}$	$b\bar{b}$, $\tau\bar{\tau}$, $c\bar{c}$
$120-160$	$WW*$, bb, ZZ^*	$WW*$, bb, ZZ^*, $[\tau\bar{\tau}]$
$160-200$	WW, ZZ (ZZ^*)	WW, ZZ (ZZ^*), $[bb]$
>200	ZZ, $[WW]$	ZZ, WW
>350	ZZ, $[tt]$, $[WW]$	ZZ, WW, $[tt]$,

The resonant production of HB at PLC and FMC seems more attractive for complete Higgs discovery, since one can obtain here many results from single experiment. So, the systematical inaccuracies are reduced substantially here.

Provided the luminosity distribution near the peak is the Lorenzian one, the cross section of the Higgs-like particle (with admixture of $\mathcal{P}$ pseudoscalar fraction) production, averaged over luminosity distribution, is ($A=\gamma\gamma$ or $\mu^+\mu^-$)

$$<\sigma_A>=\int\sigma(s)\frac{1}{\mathcal{L}}\frac{d\mathcal{L}}{ds}ds\equiv B_A\cdot 4\pi\frac{\Gamma_{H\to A}}{M_H^3}\left[1+\lambda_1\lambda_2+(1-2\mathcal{P})C_\perp\right], \quad (1)$$

$$B_A=\frac{1}{\pi}\frac{M_H}{\Gamma_H+\Delta E};\quad 4\pi\frac{\Gamma_{H\to\mu\mu}}{M_H^3}=\frac{m_\mu^2}{2v^2M_H^2},\quad 4\pi\frac{\Gamma_{H\to\gamma\gamma}}{M_H^3}=\left(\frac{\alpha}{4\pi}\right)^2\frac{|\Phi|^2}{4v^2}\quad(|\Phi|\sim 1).$$

Here $C_\perp=\ell_1\ell_2\cos 2\phi$ for photons (ℓ_i are degrees of photon linear polarization and ϕ is the angle between them) and $C_\perp=4\vec{s_{1\perp}}\vec{s_{2\perp}}$ for muons ($\vec{s_{i\perp}}$ are transverse components of muon spin).

Since $\alpha/4\pi\sim m_\mu/v$, this equation shows that the difference between cross sections at PLC and FMC is given mainly by the collider quality factor B_A. With the identical total luminosity, FMC provides higher number of Higgses produced for $M_H<400$ GeV.

1.4 The complete discovery of HB

Let us discuss the problems related to the complete discovery of HB in respect to potential of different colliders.

1. **Discovery of something and mass measurement**

This discovery is the necessary first step. The precise value of mass seems not so fundamental. However, if $M_H>130$ GeV, the $\mathcal{MSSM}$ is almost excluded.

In most of cases possible accuracy in the Higgs mass is determined by detector resolution, ratio signal/background and the value of the HB total width. The FMC provides opportunity to find the

HB mass with very high accuracy that is determined by energy spread of collider. The price for this opportunity is the fact that this collider can find HB with $M_H < 200$ GeV only **after** discovery of some signal at another collider.

2., 3. **Spin S and $\mathcal{CP}$ parity**

If $S \neq 0$, then a founded particle is not HB. The possibilities $S = 1$ or $S = 2$ should be eliminated.

If an observed particle is pseudoscalar, it is not expected HB. If, additionally, it is decoupled from gauge bosons, one can hope that it is a pseudoscalar Higgs partner from some two–doublet scheme.

At not too high mass of HB it will be discovered at e^+e^- or proton collider via *associative production*, in the channels ZH, WH, $t\bar{t}H$. The angular distributions relative to Z, W or $t\bar{t}$ are sensitive to the spin and parity of produced particle. (One can resolve scalar from pseudoscalar or vector; the opportunity to produce spin 2 particle was not considered [2, 3]). Such experiment needs large additional luminosity integral.

Another method of spin and $\mathcal{CP}$ testing at these colliders need huge luminosity integral. In this method one should study the spin correlations in the Higgs decay products (1), i.e. the azimuthal distributions in the decays like $H \to b\bar{b} \to \{b \text{ decay products}\}$).

The PLC and FMC allow best opportunities to test spin and parity of produced particle via variation of initial polarization state of system (1). With variation of sign of helicity of one photon or muon the production of "Higgs boson" is switched on or off. The variation of linear (transverse) polarizations switches on or off production depending on the parity of this particle. The C–parity will be tested via existence of $H \to WW$ decay mode.

The PLC is better for these problems due to higher degree of beam polarization expected.

4. **Coupling of HB to other particles**

The Higgs mechanism of particle mass origin in the $\mathcal{SSM}$ means that the coupling constant of HB with a fundamental particle f is given by the ratio of its mass to the vacuum expectation value of Higgs field v:

$$g_f = m_f/v, \quad v = 246\ GeV. \tag{2}$$

If the observed value will be different, then either some model with many Higgses (e.g. $\mathcal{MSSM}$) is valid or the mechanism of mass origin in $\mathcal{SM}$ differs from that considered in this model.

There are two opportunities to measure the ratios of these coupling constants. The first one can be realized at different colliders — to this end one should resolve HB signal not only in the dominant decay mode but in another modes. The difficulty is that the nonresonant production of these very final states gives very high background. This background is suppressed in the resonance production of narrow HB with not too high mass. Here the position of FMC seems the best. Very good potential (which is not studied in detail yet) has here the PLC. Another opportunity will be realized at the Hadron collider at $M_H < 150$ GeV where one can expect to resolve different production channels (ZH, WH, $t\bar{t}H$). The absolute values of these coupling constants can be obtained via direct measurement of total Higgs width at FMC (if $M_H < 250 \div 300$ GeV) and at all colliders if $M_H > 300$ GeV.

The above tables show opportunities of different colliders in this problem (see also [11]). Measurings of separate coupling constants and the Higgs selfcoupling are very difficult problems at e^+e^- or Hadron colliders (if $M_H > 150$ GeV). It needs very high luminosity integral.

5. **Higgs self– coupling**

The selfinteraction $\lambda^2(aH^3 + H^4)/8$ is the basic point of Higgs mechanism. The $\mathcal{SSM}$ constants here are $\lambda = M_H/v$ and $a = 2v$.

The HB selfinteraction can be seen in principle in the processes $\gamma\gamma \to WWHH$, $e^+e^- \to \nu\bar{\nu}HH$, $\mu^+\mu^- \to \nu\bar{\nu}HH$, etc with cross section about 1 fb or less. In these cross sections the diagrams with HHH vertex compensate strong by those without this vertex. So, the result is sensitive to possible deviations from the above value of this constant (see e.g. [14]).

The better way is to study this selfinteraction n the process $\gamma\gamma \to HH$ with cross section about 10 fb. Here the standard virtual Higgs production with the subsequent decay $H^* \to HH$ interfere with 4–legs loop diagram $\gamma\gamma HH$ (see calculations of [16]).

6. **The total width Γ_H**

In the $\mathcal{SSM}$ this value is calculated with high accuracy via M_H and the set of fundamental particle masses. Depending on M_H, (with accuracy about 10%) it reflects for the one or two coupling constants g_f only. At $M_H < 300$ GeV this quantity can be measured directly at FMC only. In the mass interval $M_H = 180 - 210$ GeV the cross section of the process $\gamma\gamma \to WW$ exhibit specific structure odue to interference of QED process with HB. With resolution about 5 GeV in the WW effective mass this structure can be used both to see the Higgs boson and to measure its width.

At $M_H > 300$ GeV the HB width can be measured, in principle, with the reasonable resolution of detector.

7. **The two–photon width $\Gamma_{\gamma\gamma}$**

In the $\mathcal{SSM}$ the two–photon width of HB depends strongly on the number of fundamental particles in the $\mathcal{SM}$ that are heavier than HB itself. With new heavy vector meson (similar to W) this width is enhanced by a factor $3 \div 100$ depending on M_H. With heavy 4-th generation (with heavy neutrino) the change of this width is given by a factor which varies from 1/2 to 10 (depending on M_H). Therefore, one can sayu that $\Gamma_{\gamma\gamma}$ is the **counter** *of particles that are heavier than HB itself.* The same is valid for the gluon fusion HB production at proton collider. Its cross section is very sensitive to the possible existence of 4-th generation [18]. Fig. 1 shows the corresponding variations in the $\gamma\gamma \to H$ cross section.

At hadron colliders the value of $\Gamma_{\gamma\gamma}$ can be obtained with low accuracy at $M_H < 150$ GeV [2]. This value cannot be obtained at e^+e^- collider and (probably) at MC.

Provided the $\mathcal{SSM}$ is valid for dominant decay of HB, one can extract Higgs two–photon width $\Gamma_{\gamma\gamma}$ from its production cross section at PLC (this opens an interesting opportunity to use $\Gamma_{\gamma\gamma}$ as the counter of particles that are heavier than HB.)

8. **Anomalous interactions of HB**

Last point is beyond the story about complete discovery of HB.

If HB will be discovered, one should consider the next problem: *Can we obtain via HB some signals from underlying interactions, with scale $\Lambda \geq 1$ TeV?*

The PLC ($\gamma\gamma$ and γe) have very high potential in this problem. Indeed, at energies below Λ these underlying interactions will manifest themselves as some anomalous interactions of presently known particles. These anomalies cause corrections to the observed interactions. In almost all cases these corrections are relatively small in comparison with interactions initially existent in the $\mathcal{SM}$. The interactions of Higgs with photons ($H\gamma\gamma$ and $HZ\gamma$) provide a new opportunity, since in the $\mathcal{SM}$ these interactions arise only at the loop level. In other words, the relative contribution of anomalous effects from underlying interactions (if they exist) will be enhanced in the processes $\gamma\gamma \to H$, $\gamma e \to eH$ only. Some example was discussed in respect to the effect of very heavy particles in the HB two–photon width. More detailed treatment can be found in refs. [17, 19].

1.5 Conclusion

As a result, we compare the discovery potential of different colliders for HB in two tables.

One can see that the PLC and FMC are the best machines for the complete discovery of HB with some advantages fof PLC. The analysis of the data in Z peak and estimates in the $\mathcal{MSSM}$ show that the most probable mass interval for HB is $100 \div 200$ GeV. So, as it was proposed earlier [20], the PLC with the c.m.s. energy 100–200 GeV open the shortest way to find HB and to test its properties completely.

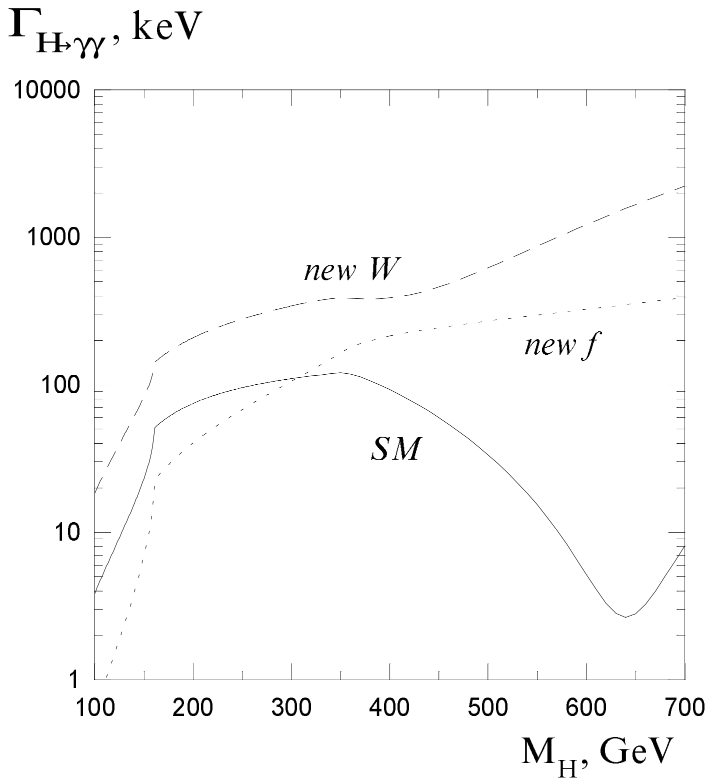

Fig. 1 Higgs boson two photon width in SM
and with new heavy particles:
new W boson (dashed line)
and new fermion generation (dotted line).

problem	Tevatron/ LHC	e^+e^- LC	PLC	FMC
Discovery some particle	+	+	+	—
Mass	+	+	+	The best
Spin	±	±	The best	+
$\mathcal{CP}$ parity	±	±	The best	+
Set of coupling constants	+	+	+	+
Self–interaction	—	±	+ (nonresonant)	±
Γ_{tot}	—	—	—	Good
$\Gamma_{\gamma\gamma}$	Poor	—	Good	—
4 generation	Good	—	Good	—
Extra W	±	—	Good	—
Anomalies	—	—	Good	—

Potential of Higgs discovery for $M_H < 200$ *GeV*

<table>
<tr><th>problem</th><th>Tevatron/
LHC</th><th>e^+e^- LC</th><th>PLC</th><th>FMC</th></tr>
<tr><td>Discovery some particle</td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>Mass</td><td>+</td><td>+</td><td>+</td><td>The best</td></tr>
<tr><td>Spin</td><td>±</td><td>±</td><td>The best</td><td>+</td></tr>
<tr><td>$\mathcal{CP}$ parity</td><td>±</td><td>±</td><td>The best</td><td>+</td></tr>
<tr><td>Set of coupling constants</td><td>Poor</td><td>±</td><td>±</td><td>±</td></tr>
<tr><td rowspan="2">Self–interaction</td><td rowspan="2">—</td><td rowspan="2">±</td><td>+</td><td>±</td></tr>
<tr><td colspan="2">(nonresonant)</td></tr>
<tr><td>Γ_{tot}</td><td>Poor</td><td>±</td><td>±</td><td>Good</td></tr>
<tr><td>$\Gamma_{\gamma\gamma}$</td><td>—</td><td>—</td><td>The best</td><td>—</td></tr>
<tr><td>4 generation</td><td>Good</td><td>—</td><td>Good</td><td>—</td></tr>
<tr><td>Extra W</td><td>—</td><td>—</td><td>Good</td><td>—</td></tr>
<tr><td>Anomalies</td><td>—</td><td>—</td><td>+</td><td>—</td></tr>
</table>

Potential of Higgs discovery for 200 GeV $< M_H <$ 500 *GeV*

1.6 Some estimates for PLC

At the end we estimate necessary luminosity integral for the discovery of HB in the wide mass interval at PLC. We assume here the sequence of runs, each of them covers about 10 % of energy near the upper bound. Fig. 2 represent the HB production cross section for different dominant channels here.

If $M_H < 145$ GeV, the discovery of HB via reaction $\gamma\gamma \to b\bar{b}$ demands luminosity integral less than 3 fb^{-1} for suitable energy interval [12]. If $135 < M_H < 195$ GeV, the discovery of HB via reaction $\gamma\gamma \to WW^*$ demands luminosity integral less than 1 fb^{-1} for suitable energy interval [7]. If $M_H > 185$ GeV, the discovery of HB via reaction $\gamma\gamma \to ZZ$ demands luminosity integral less than 1 fb^{-1} for suitable energy interval. So, to cover mass interval 100–200 GeV, one should have luminosity integral less than 15 fb^{-1}.

After discovery of Higgs peak, the same luminosity integral (no more than 3 fb^{-1}) is necessary to test spin and parity of this particle via the change of polarization (see eq. (1)).

Depending on the Higgs mass, the detailed studies of another decay modes permit to find the ratios of coupling constants of HB with other particles. For example, about 10 fb^{-1} is necessary to see decay $H \to ZZ^*$ at $M_H > 120$ GeV [7]. So, one can find the ratio g_{HZZ}/g_{HWW}. If the HB mass is within interval 125–150 GeV, one can measure additionally $g_{Hb\bar{b}}/g_{HWW}$, etc. This interval is the best for testing of many coupling constants of HB.

In the subsequent mass interval 200–500 GeV the main discovery channel is $\gamma\gamma \to ZZ$ with necessary luminosity integral about 1 fb^{-1} for each energy interval. So the luminosity integral less than 10 fb^{-1} is necessary to cover the whole discussed region. The additional integral about 2 fb^{-1} is necessary to test spin and parity here.

2 Some physical problems for future μp colliders

I consider here physical potential of the specific mode of $\mu^+\mu^-$ collider — $\mu^- p$ collider. This collider can be obtained from the basic $\mu^+\mu^-$ device if accelerate specifically prepared initial protons instead of μ^+. This operation seems not so expensive.

The final proton energy will be the same as that of μ^+ and luminosity of this new collider will be the same or even larger than that of the basic $\mu^+\mu^-$ collider (since the number of protons can be larger than the number of muons). The muon polarization is necessary for this collider. This collider is of interest for the beam energy $E \geq 200$ GeV (more than HERA).

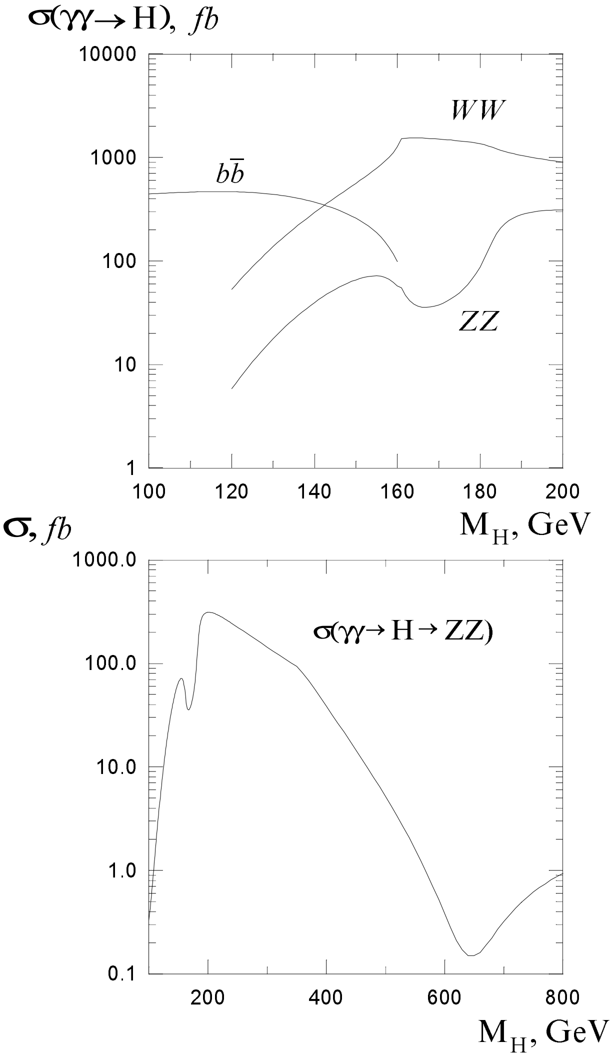

Fig.2 The cross section of the process $\gamma\gamma \to H$ for different final states.

This collider has much higher physical potential than the now discussed LINAC–RING *ep* colliders due to much higher luminosity.

Simultaneously, one can consider μp collider in which muon beam from $\mu^+\mu^-$ collider collides with proton beam from the TEVATRON ring, if its luminosity will be high enough.

The discussed collider is a supplement to the $\mu^+\mu^-$ collider, it will be operate after that collider and after LHC. Therefore, the number of really new problems of particle physics that can be solved here, is not so high. So, I discuss the problem:

What really new can be studied at μp collider AFTER studies at basic $\mu\mu$ collider and the LHC collider

2.1 Basic points

Let us enumerate characteristic new features of this collider.

1. New type of collisions — μp instead of the existing ep.
2. Lepton–proton collision in new energy domain (the same as in the basic $\mu^+\mu^-$ collider).
3. High luminosity (the same as for the basic $\mu^+\mu^-$ collider or larger by a factor $3 \div 10$).
4. Large enough degree of muon polarization (I expect about 60%).
5. Small energy loss due to bremsstrahlung.

The high monochromaticity of muons is unnecessary for this collider.

2.2 QCD and hadron physics. Continuation of studies at HERA

Structure functions, etc. There is large list of modern studies here, which will be continued at this machine. Large extension of the studied region in the x, Q^2 space is provided by much higher energy and luminosity (points 2, 3), much more accuracy in the results is expected due to practical absence of Initial State Radiation (point 5).

Breaking of the factorization. The cross sections for production of heavy particles or events with high $p_\perp$ in pp or $p\bar{p}$ collision are written usually in the simple factorizable form like

$$\sigma \propto \int f(x_1, Q^2) f(x_2, Q^2) \hat{\sigma}(x_1 x_2 s) \tag{3}$$

with factorization of parton densities. At small enough values of x_i this factorization should be broken (see e.g. [21]). This phenomenon is close to the effect of unitariztion of BFKL Pomeron.

The expected high accuracy of data at μp collider together with data from LHC provides opportunity to see in detail this breaking.

The study of *hard diffractive processes* provides opportunity to test pQCD and to investigate perturbative Pomeron and Odderon in reactions

$$\gamma p \to \rho^0 + ..., \quad \gamma p \to (q\bar{q}) + ..., \quad \gamma p \to \gamma + ..., \gamma p \to \pi^0 + ... \textit{with rapidity gap.} \tag{4}$$

It is stated now [22] that the real region of the pQCD validity begins at very high $p_\perp \geq 7 \div 10$ GeV — the cross section here is very small. This region becomes achievable due to higher luminosity and energy (points 2, 3). Besides, the pQCD becomes valid at lower $p_\perp \geq 3 \div 4$ GeV in the hard Compton effect with a rapidity gap; the cross section here is not so small. However, in ep collisions the extraction of this hard Compton from the data is a very difficult task due to strong bremsstrahlung from electron. This background reduces strongly at μp collision. So, this process can be studied here (point 5). One can expect to see here the regime of BFKL Pomeron (if it exists) and its unitarization (a good theory of this effect based on pQCD is absent till now).

2.3 Structure function from Z — axial structure function

The studied process is

$$\mu_{\uparrow\downarrow} p \to \mu + ... \quad (Q^2 = -(p_\mu - p_\mu^{'})^2). \tag{5}$$

The discussed structure function differs from that usually used (vector structure function) more strongly than it is assumed usually due to axial current anomaly (at $Q^2 < m_q^2$ — $q = c, b, t$). The opportunity of these studies is provided by high energy and luminosity together with variable longitudinal polarization of muons (points 2, 3 and 4 together with 5).

The standard DIS experiment with polarized muons at high Q^2 is described by diagrams with both photon and Z exchange (contribution of other diagrams is negligible). Let σ^L and σ^R abe the cross sections for the left–hand and right–hand polarized muon. One can connect these cross sections with contributions of vector current M_V and axial current M_A. The last obliged by interaction with photon (J^γ) and Z (J^Z):

$$M_V = \frac{1}{Q^2} J^\gamma + \frac{1/4 - \sin^2\Theta_W}{Q^2 + M_Z^2} J_V^Z; \quad M_A + \frac{1}{Q^2 + M_Z^2} J_A^Z. \tag{6}$$

(We see that in good approximation $M_V \propto J^\gamma$.)

With these notations

$$\sigma_{L,R} \propto |M_V \pm M_A|^2;$$
$$\Delta\sigma = \sigma^L - \sigma^R \propto Re(M_V^* M_A), \quad \sigma^{np} = \frac{\sigma^L + \sigma^R}{2} \propto |M_V|^2 + |M_A|^2. \tag{7}$$

The difference $\Delta\sigma$ should be not small in comparison with separate cross sections σ^L and σ^R at $Q^2/M_Z^2 \gg 0$, for example, at $Q^2 > (1 \div 3) \cdot 1000$ GeV^2. Therefore, the reliable accuracy in the extraction of axial contribution is possible here.

2.4 Structure functions for charged current

Let us consider the process

$$\mu p \to \mu W + ... \tag{8}$$

At $p_{\perp\,\mu}, p_{\perp\,W} \lesssim M_W$ the diagramm with W exchange between virtual photon (or Z) and hadrons is dominat. One can study here the charged current interaction with hadrons with the KNOWN ENERGY of exchanged W. This opportunity is very new in comparison with the modern studies of process like $\mu p \to \nu + X$, where the energy of W is unknown. Until now we have here only calculations in the parton model with very rough testing. The detailed calculations for this process are in progress.

This opportunity is due to large energy and the luminosity (points 2, 3).

2.5 Leptoquarks, etc

This collider gives really new opportunity to see leptoquark in the fusion of muon with quark from proton (mainly, s or c).

It is natural (only NATURAL) to expect that the coupling of this "light" leptoquark with quarks and leptons is similar to that in Yukawa interaction of quark with Higgs (produced the Higgs mass) [1]:

$$g_{\ell q} \sim \left(\frac{m_\ell + m_q}{v}\right) |S_{\ell q}| \text{ with } v = 1\sqrt{/}G_F\sqrt{2} = 246 \text{ GeV}. \tag{9}$$

Besides, it seems to be natural that the mixing between generations is small, and the masses of muon and s or c quarks are summed here. Therefore, the expected rate of "electroquarks" is very low, and their discovery in such experiments seems to be hardly probable. On the other hand, for the "muoquark" this coupling constant becomes not so small,

$$g_{\mu c} \sim 0.005, \quad g_{\mu s} \sim 0.002,$$

and one can expect here a visible effect (if such muoquark exists).

There is a limited list of new opportunities here related to discovery of other new particles (SUSY, etc.). The simple example provides **gluino search** in the reaction

$$\gamma g \to \tilde{\gamma}\tilde{g} \tag{10}$$

The expected high luminosity here provides high potential for gluino discovery in this process.

The resonance-like production with decay two sparticles becomes possible here, if some SUSY theory with R-parity breaking is true.

The specific muon–quark contact interaction can be seen here via the almost homogeneous angular distribution of obtained μ and quark (jet).

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[1]Certainly, the less natural models with not too small $g^{\ell q}$ cannot be excluded and the search of leptoquark should be continued here.

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