GAMMA FACTORY AND PRECISION PHYSICS AT THE LHC*

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In this paper, we argue that the only way to improve systematic precision of W-boson mass and weak-mixing angle measurements at the LHC is to replace proton beams with isoscalar-ion beams. This results in a significant simplification of relations between W- and Z-boson production processes, with the latter serving as a precision "standard candle". However, with the presently operating LHC ion injectors, partonic luminosity for ion–ion collisions is significantly lower than the one for proton–proton collisions. Therefore, statistical precision of the above measurements is lower for the former case. The proposed way out to improve the partonic luminosity in the ion–ion mode is to transversely cool the beams. The Gamma Factory project can achieve this goal with the use of laser cooling. This will allow to improve the precision of experimental determination of the above parameters to $\delta M_W < 5$ MeV and $\delta \sin^2\theta_{\rm W} < 10^{-4}$. The proposed calcium beams are also optimal for exclusive Higgs-boson production in multiperipheral $\gamma\gamma$ collisions and studies of $H \to b\bar{b}$ decays in a clean environment.

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1. Introduction

Contemporary hadron colliders, such as the Tevatron at Fermilab [1] and the LHC [2] at CERN, are not only discovery machines but also tools for pre-

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cision measurements of important Standard Model (SM) parameters, such as the W-boson mass M_W and width Γ_W, the weak-mixing angle $\sin^2\theta_{\mathrm{W}}$, *etc.* In some cases they even surpass in this respect lepton colliders which are regarded as precision machines. A good example of this is the W-boson mass determination. At the e^+e^- collider LEP, M_W was measured with the accuracy of $\delta M_W = 33$ MeV [3], while a much higher precision of $\delta M_W = 9.4$ MeV was achieved by the CDF experiment at Tevatron [4] and of $\delta M_W = 16$ MeV by the ATLAS experiment at the LHC [5]. The main advantage of hadron colliders w.r.t. the lepton ones is much higher event statistics, while disadvantages include a larger background, more difficult event selection and reconstruction, systematic effects due to both experimental and theoretical uncertainties.

As far as the latter effects are concerned, there can also be significant differences between proton–antiproton collisions at the Tevatron and proton–proton collisions at the LHC. This can be seen in the case of the M_W measurements where the systematic error of the CDF result (6.9 MeV) is comparable to the statistical error (6.4 MeV), while for the recent ATLAS result, the systematic error (15 MeV) is by a factor of 3 larger than the statistical one (5 MeV) and by more than a factor of 2 larger than the CDF systematic error. Thus, in spite of a much higher W-boson event statistics collected by ATLAS ($\sim 14\times 10^6$) as compared to the one by CDF ($\sim 4\times 10^6$), the total error on M_W from ATLAS is by $\sim 70\%$ larger than the one from CDF. The reasons for this are explained in Section 2. There, we also propose observables and measurement methods for the LHC which can allow to reduce the main systematic uncertainties of experimental analyses related to the M_W, Γ_W, and $\sin^2\theta_{\mathrm{W}}$ measurements. In Section 3, we briefly describe the Gamma Factory project for CERN and its possible applications. In Section 4, we discuss a high-luminosity option of the LHC with laser-cooled calcium beams based on the Gamma Factory which can be used for precision physics studies. Finally, Section 5 concludes the paper.

2. Ways to reduce systematic uncertainties at the LHC

The precision target for the W-boson mass measurement at the LHC has been set at $\delta M_W \leq 5$ MeV [6, 7], which corresponds to the relative error $\delta M_W/M_W < 0.01\%$. Such a precision level constitutes a really big challenge, both for experiment and theory. The ATLAS experiment has already reached the statistical precision of 5 MeV in its M_W measurement using the low-pileup data from the LHC run in 2011 at the centre-of-mass energy of 7 TeV. Unfortunately, its systematic error is much higher, 15 MeV [5], and will be difficult to reduce for higher-pileup data collected in the LHC proton–proton (pp) runs after 2011.

At hadron colliders, M_W is determined in electron and muon decay channels of singly produced W^+/W^- bosons, *i.e.* charged-current Drell–Yan processes. Since final-state neutrinos are not detected, lepton-pair invariant mass cannot be used for that purpose, instead one has to rely on transverse-plane observables, such as charged-lepton transverse momentum $p_{\mathrm{T},l}$ and leptons transverse mass m_{T}. While the former can be measured directly using energy and polar angle of a detected charged lepton, for the latter one one has to reconstruct neutrino transverse momentum using information on transverse hadronic recoil, which is a major precision-limiting factor. For W-bosons with no transverse momentum ($p_{\mathrm{T},W} = 0$), these two observables exhibit sharp peaks: $p_{\mathrm{T},l}$ at $M_W/2$ and m_{T} at M_W. Therefore, regions near these peaks can be used for the W-mass fits. Unfortunately, these peaks are smeared by QCD and detector effects, reducing their sensitivity to M_W. $p_{\mathrm{T},l}$ is affected mainly by the QCD effects and much less by the detector ones, while for m_{T} it is the opposite. Therefore, for $p_{\mathrm{T},l}$, the theory uncertainties are dominant, while for m_{T}, the experimental uncertainties dominate.

In a series of papers [8–11], we investigated possibilities of precision measurements of electroweak (EW) Standard Model (SM) parameters at the LHC, in particular the W-boson mass M_W, and also the mass difference between positively and negatively charged W bosons: $\Delta M_W = M_{W^+} - M_{W^-}$. All these studies were performed with the use of the Monte Carlo generator WINHAC [12] dedicated to charged-current Drell–Yan processes with multiphoton radiation based on the Yennie–Frautschi–Suura (YFS) exclusive exponentiation [13] and including the NLO EW corrections [14]. In these papers, we discuss differences between the Tevatron and the LHC concerning the Drell–Yan processes and their effects on systematic uncertainties of basic W- and Z-boson observables. At the Tevatron, due to (1) the CP symmetry of the W^+ and W^- production and decay processes, (2) similar quark contributions to W and Z production dominated by valence quarks, and (3) values of the EW couplings, distributions of the main observables for the sum of $W^+ + W^-$ processes are very similar to the ones of the Z process (when adjusted for the mass difference M_W/M_Z). Therefore, the measurement of the W-boson mass can be based on ratios of the $W^+ + W^-$ to Z observables in which most of the systematic uncertainties cancel, among them the ones related to the perturbative and non-perturbative QCD effects which are common for the $W^+ + W^-$ and Z processes. This cannot be applied to the LHC, where due to asymmetry in the valence u and d quark contribution to the proton structure, and also differences in sea-quark contributions to the W^+ and W^- production processes, distributions of the W-boson observables differ considerably between W^+ and W^-. In addition, quark contributions to the Z-boson production are very different from the ones for the W^+/W^- production, in particular the b-quark contribution to the former process is at the level of 6%, while to the latter it is close to 0%.

In general, the pure sea-quark contributions to these processes at the LHC amount to $\sim 30\%$, while at the Tevatron, they were at the level of 10%. All this renders controlling the systematic uncertainties in the W-boson mass measurement at the LHC is much more difficult than at the Tevatron. This can be seen in the recent results for M_W determination of the ATLAS and CDF experiments, where in spite of more than a factor of 3 higher W-boson event statistics collected by ATLAS, its systematic error (15 MeV)[1] is by more than a factor of 2 higher than that of CDF (6.9 MeV).

In the above papers, we propose dedicated observables and experimental strategies that can allow to measure M_W with the precision below 10 MeV. The proposed four observables are two asymmetries and two ratios of differential cross sections corresponding to the final-state charged leptons (electrons and muons) being the decay products of singly produced W^+, W^-, and Z bosons. They are sensitive to the EW SM parameters, such as M_W, Γ_W, as well as their differences between W^+ and W^-, and $\sin^2\theta_{\rm W}$, while at the same time they are almost insensitive to strong-interaction and detector effects. Thus, they allow to reduce systematic uncertainties in measurements of the above parameters, such that their precision targets of the LHC experiments can be achieved.

Unfortunately, for the pp collision mode of the LHC, with the above four observables, three degrees in flavour-dependent parton distribution functions (PDFs) remain unconstrained: $u_v(x) - d_v(x)$, $c(x) - s(x)$, and $b(x)$, where v stands for valence quarks and x is the Bjorken scaling variable. In such a case, the LHC data have to be supplemented with an external input: the Tevatron data and a dedicated muon–nucleon deep-inelastic scattering (DIS) experiment, which can be conducted *e.g.* at COMPASS (CERN). Without such external data, the precision $\delta M_W < 12$ MeV cannot be achieved, even in the high-luminosity pp LHC phase. In [11], we show that this can be done with the LHC data alone, if proton beams in the LHC are replaced with isoscalar-ion beams, such as deuteron beams. The isoscalar-ion beams, in which the number of protons is equal to the number of neutrons, profit from flavour symmetry of the strong interactions to equalise distributions of the u and d quarks. As a result, the effects of PDFs uncertainties on the proposed observables are reduced by a factor of 10–50. However, in order to reach $\delta M_W \sim 5$ MeV, one would need the integrated nucleon–nucleon luminosity > 100 pb^{-1}. Unfortunately, with the current CERN accelerator infrastructure, this is impossible to achieve for the deuteron beams. Therefore, in Ref. [15], we considered the isoscalar calcium beams and showed that if a Gamma-Factory-based laser cooling is applied to such beams, one can get a sufficient luminosity, even ~ 1000 pb^{-1}. This is discussed in the following sections.

[1] In our opinion, it is rather optimistic.

3. Gamma Factory at CERN

The basic idea of the Gamma Factory (GF) project for CERN was proposed in Ref. [16]. Studies related to this project are anchored in and supported by the Physics Beyond Colliders (PBC) framework at CERN [17]. To date, about 100 physicists and engineers from about 40 institutions worldwide have contributed to these studies.

The main concept of GF is presented in Fig. 1. Laser photons with momentum k collide with ultrarelativistic partially stripped ions (PSI) of relativistic Lorentz factor γ_{L}, mass m, velocity $v = \beta c$, where c is the velocity of light, circulating in a storage ring. Resonantly scattered photons with momentum $k_1 \gg k$ are emitted in a narrow cone with an opening angle $\theta \approx 1/\gamma_{\mathrm{L}}$ in the direction of motion of the PSI beam. PSI consists of an atomic nucleus with a few electrons left on its atomic shells. Laser photons excite these electrons to the upper atomic level by resonant absorption.

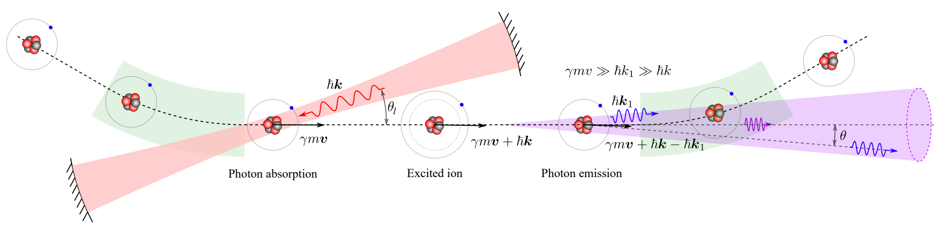

Fig. 1. The concept of the Gamma Factory.

Then, after some short time, these electrons deexcite to their ground states by spontaneous emission of photons. Since PSIs move with high velocities, close to the velocity of light, due to the double Doppler effect (during absorption and emission), these photons acquire energies that are much higher than the energy of the initial laser photons — by a factor up to $4\gamma_{\mathrm{L}}^2$. The relativistic Lorentz γ_{L} factor of PSI beams at the LHC can reach ~ 3000, so for laser photons with energy of a few keV one can produce gamma-rays with energy of hundreds of MeV, *i.e.* about 3 orders of magnitude higher than in FEL facilities. Since the energy of PSI is several orders of magnitude higher than the energy of the absorbed and emitted photons, the LHC accelerator RF power can be in almost 100% converted into the power of produced gamma-ray beams. Because of this, the intensity of a photon beam generated at GF can match those of the best FEL facilities, such as DESY XFEL. Due to a ultrarelativistic boost at the emission stage, the GF photons are strongly collimated — about a half of them are emitted within a polar angle $\theta \approx 1/\gamma_{\mathrm{L}}$ w.r.t. the PSI-beam direction, which for the LHC corresponds to angles below 1 mrad. By using circularly polarised laser photons, one can produce circularly polarised gamma-ray beams, with up to 99% degree of polarisation [18]. More details on GF can be found *e.g.* in Refs. [19–21].

The GF photon beams can be sent through slit collimators to collide with special fixed targets and produce tertiary beams of polarised electrons, polarised positrons, polarised muons, pions, neutrinos, neutrons, and radioactive ions with intensities that are up to 4 orders of magnitude higher than those available at currently operating sources, see *e.g.* [18].

There is a multitude of possible applications of GF research tools in many domains of basic and applied science, such as:

— particle physics: precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode using laser-cooled calcium-ion beams, rare muon decays, precision neutrino physics, QCD-confinement studies, *etc.*

— nuclear physics: nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides, *etc.*

— atomic physics: highly charged atoms, electronic, muonic, pionic, and kaonic atoms, *etc.*

— astrophysics: dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ reaction, and S-factors, *etc.*

— fundamental physics: studies of the basic symmetries of the universe, atomic interferometry, *etc.*

— accelerator physics: beam cooling techniques, low-emittance hadronic beams, plasma wake-field acceleration, high-intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow-band and flavour-tagged neutrino beams, neutron sources, *etc.*

— applied physics: accelerator-driven energy sources, nuclear fusion research, medical isotope, and isomer production, *etc.*

More information on physics opportunities of GF can be found in [22].

Currently, we are preparing for the Proof-of-Principle (PoP) experiment at the SPS with lithium-like lead-ion ($^{208}_{82}\mathrm{Pb}^{79+}$) beams [23]. Its main goals are to demonstrate: (1) that an adequate laser system (5 mJ @ 40 MHz) can be (remotely) operated in the high-radiation field of the SPS; (2) that very high rates of photons are produced: almost all ions are excited in a single collision of a PSI bunch with a laser pulse; (3) stable and repeatable operation; (4) laser ion-beam cooling: longitudinal and transverse, as well as (5) confront data with simulations, and (6) perform some new atomic physics measurements. The planned installation time of this experiment is the LHC long shut-down 3 (LS3) in 2026/2027.

4. Laser-cooled isoscalar ion beams at the LHC

Instantaneous luminosity of colliding particle beams is inversely proportional to the function β^*, which is a measure of transverse beam size at an interaction point (IP), and the beam emittance ε, which is a measure of transverse beam size and divergence

$$\mathcal{L} \propto 1/\sqrt{\beta_x^* \beta_y^* \, \varepsilon_x \varepsilon_y}\,. \tag{1}$$

There are two complementary ways to increase collider luminosity: (1) by increasing focusing strength of magnets at IP, leading to decreasing of β^*, which is to be realised in the ongoing HL-LHC project for *pp* collisions, and (2) by reducing the beam emittance ε, which can be realised using beam-cooling techniques.

In Ref. [15], we proposed a new way of cooling high-energy ion beams by exploiting the Doppler effect in atomic absorption/emission of photons by partially stripped ions. This so-called Doppler cooling, or laser cooling, is well known and commonly used in atomic physics to cool stationary atoms. Its main idea is to use three pairs of "red-detuned" lasers placed in three orthogonal directions and shining towards trapped atoms. "Red detuning" means that their frequency is lower than a resonant absorption frequency of still atoms, therefore only the atoms that move towards a laser with a certain velocity can be resonantly excited due to the Doppler effect. Then, such atoms deexcite by radiating photons in arbitrary directions which results in decreasing of atoms velocity in the laser direction. Since there are six lasers shining from three orthogonal spatial directions, this leads to cooling of the trapped atoms, *i.e.* damping of their thermal movements.

The same idea can be applied to ultrarelativistic beams of partially stripped ions in the Gamma Factory. One can use a "red-detuned" laser, such that a fraction of PSIs moving forward with velocities higher than the average bunch velocity can absorb laser light. In this way, one can achieve longitudinal cooling of a PSI beam. This kind of cooling can be efficient and fast, as shown in Fig. 2 for a lithium-like calcium ($^{40}_{20}\mathrm{Ca}^{17+}$) beam, see [15] for more details. However, to reduce beam emittances ε_x and ε_y, we need the cooling in the transverse directions x and y. Cooling in the x direction can be achieved by the so-called dispersive coupling, *i.e.* using a second laser and shifting slightly its focal point in the x direction towards the collider ring centre [24]. In Ref. [15], we found that a laser-pulse shift by 1.4 mm provides the optimal coupling of horizontal betatron oscillations to (longitudinal) synchrotron oscillation. As a result, about 17% of all PSIs are excited in each bunch crossing. Vertical betatron oscillation can be damped by coupling them to the horizontal ones using the transverse betatron coupling resonance, which happens when their frequencies are close to each

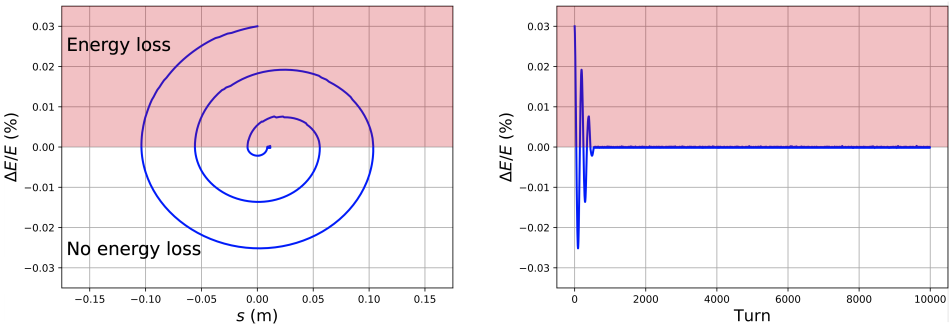

Fig. 2. Simulations of longitudinal cooling of lithium-like calcium beam.

other. Thus, in order to achieve the PSI-beam cooling in the longitudinal and transverse directions, two lasers are needed: (1) the first one for the dispersive coupling with a photon beam shifted towards the negative horizontal position with respect to the PSI-beam centre and broad frequency spectrum allowing to excite the PSIs over the full spread of their energies, and (2) the second one with a focal point centred on the ion-beam axis and a frequency band tuned to excite only the PSIs with higher-than-average longitudinal momenta. The actual beam cooling is proposed to be performed in the SPS, and the remaining electrons are to be stripped in the SPS-to-LHC transfer line. Then, the fully stripped Ca ions will be accelerated to the top LHC energy, and the optical stochastic cooling may be applied, if necessary.

Numerical results of our simulation for the lithium-like calcium beam cooling are shown in Fig. 3. As one can see, a factor of 5 reduction of the transverse emittance can be achieved in a time of 8 s. With 3×10^9 ions per bunch and 1404 bunches per beam, this is sufficient to reach the instantaneous nucleon–nucleon luminosity of calcium-ion beams at the LHC

$$\mathcal{L}_{NN} = 4.2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\,, \tag{2}$$

which is comparable to the expected luminosity of pp collisions at the HL-LHC. The advantage of the Ca beams is a much lower pile-up than for proton beams: ~ 5 collisions per Ca–Ca beam crossing *versus* ~ 700 collisions per pp beam crossing for the same luminosity $\mathcal{L}_{NN}$.

By sharing the HL-LHC running time in proportions of 2/3 for the pp collisions and 1/3 for the Ca–Ca collisions, one could obtain the integrated nucleon–nucleon luminosity of ~ 1000 fb^{-1} in the latter case. This would allow to measure the W-boson mass at the LHC with the precision of $\delta M_W < 5$ MeV and the weak-mixing angle with the precision of $\delta \sin^2\theta_{\mathrm{W}} < 10^{-4}$. The Ca–Ca collisions also maximise photon fluxes for exclusive Higgs-boson production in multiperipheral $\gamma\gamma$ collision at the LHC.

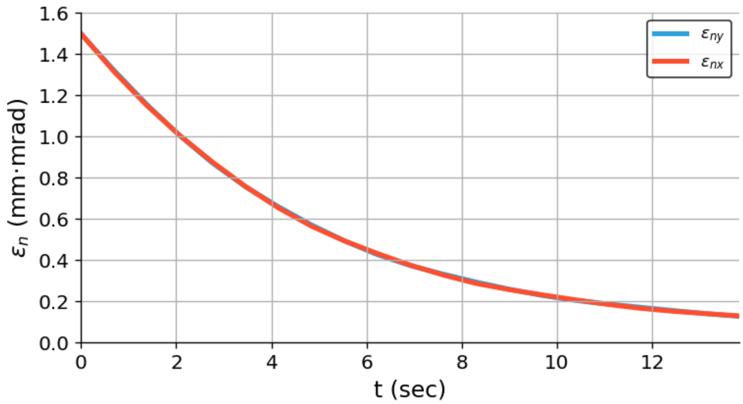

Fig. 3. Simulations of transverse cooling of lithium-like calcium beam. The time-evolution curves of the vertical and horizontal emittances overlap each other — they are precisely equal when the betatron tunes are on the coupling resonance.

With the above luminosity, ~ 420 Higgs bosons can be collected per experiment, giving a unique possibility for studies of the $\gamma\gamma \to H \to b\bar{b}$ process in a clean environment. More details can be found in Ref. [15].

5. Conclusions

In this paper, we have discussed prospects of improving the precision of experimental determination of the electroweak Standard Model parameters, such as the W-boson mass M_W and the weak-mixing angle $\sin^2\theta_{\rm W}$. We have argued that dealing with systematic effects at the LHC is much more difficult than at the Tevatron, because processes of W^+ and W^- production are not CP symmetric for pp collisions and they cannot be easily related to Z-boson production. Moreover, sea-quark contributions to these processes are much higher at the LHC than at the Tevatron, and different for W^+, W^-, and Z. Therefore, reaching the precision of $\delta M_W < 12$ MeV in pp collisions at the LHC will not be possible without an external input from other experiments, *e.g.* Tevatron and a dedicated muon–nucleon DIS experiment. We have shown that this could be possible if instead of pp, isoscalar-ion beam collisions are used, however, this requires high integrated nucleon–nucleon luminosity, > 100 pb^{-1}. Such a luminosity can be achieved with the isoscalar calcium-ion beams, if the laser cooling based the Gamma Factory is applied to partially stripped calcium ions. If a fraction of 1/3 of the HL-LHC running time is allocated to this option, one can achieve integrated nucleon–nucleon luminosity ~ 1000 pb^{-1}. This would allow to reach the precisions of $\delta M_W < 5$ MeV and $\delta\sin^2\theta_{\rm W} < 10^{-4}$, which would constitute a considerable improvement in the experimental determination of these parameters — important for consistency tests of the Standard Model and searches for possible new physics.

Calcium-ion beams are also optimal for exclusive Higgs-boson production in multiperipheral $\gamma\gamma$ collisions at the LHC and precision studies of the Higgs coupling to b-quarks with low background.

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