Generation of arbitrarily polarized GeV lepton beams via nonlinear Breit-Wheeler process

Kun Xue,[1] Ren-Tong Guo,[1] Feng Wan,[1] Rashid Shaisultanov,[2,3] Yue-Yue Chen,[4] Zhong-Feng Xu,[1] Xue-Guang Ren,[1] Karen Z. Hatsagortsyan,[2,*] Christoph H. Keitel,[2] and Jian-Xing Li[1,†]

[1] *MOE Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter, School of Physics, Xi'an Jiaotong University, Xi'an 710049, China*

[2] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

[3] *Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

[4] *Department of Physics, Shanghai Normal University, Shanghai 200234, China*

(Dated: January 7, 2022)

Generation of arbitrarily spin-polarized lepton (here refer in particular to electron and positron) beams has been investigated in the single-shot interaction of high-energy polarized γ photons with an ultraintense asymmetric laser pulse via nonlinear Breit-Wheeler (BW) pair production. We develop a fully spin-resolved semi-classical Monte Carlo method to describe the pair creation and polarization in the local constant field approximation. In nonlinear BW process the polarization of created pairs is simultaneously determined by the polarization of parent γ photons, the polarization and asymmetry of scattering laser field, due to the spin angular momentum transfer and the asymmetric spin-dependent pair production probabilities, respectively. In considered all-optical method, dense GeV lepton beams with average polarization degree up to about 80% (adjustable between the transverse and longitudinal components) can be obtained with currently achievable laser facilities, which could be used as injectors of the polarized e^+e^- collider to search for new physics beyond the Standard Model.

Ultrarelativistic spin-polarized lepton (here refer in particular to electron and positron) beams have many important applications in particle and high-energy physics [1–3], especially in e^+e^- collider, such as International Linear Collider (ILC) [4, 5], Compact Linear Collider (CLIC) [6, 7] and Circular Electron Positron Collider (CEPC) [8, 9]. In those experiments, the longitudinal polarization of leptons can change interaction cross section and consequently provides high sensitivities [4] through, e.g., suppressing background from WW boson and single Z boson production via WW fusion [4], enhancing different triple gauge couplings in WW pair production [4, 10] and improving top vector coupling in top quark production [11]; while, the transverse polarization can cause asymmetric azimuthal distribution of final-state particles [12] and then brings a way to study new physics beyond the Standard Model (BSM) [13–16] through, e.g., measuring relative phases among helicity amplitudes in WW pair production [17], probing mixture of scalar-electron states [18] and searching for graviton in extra dimensions [19]. Commonly, longitudinal and transverse polarizations are studied separately since those corresponding effects are independent to each other [4, 12]. However, it deserves to point out that the arbitrarily spin-polarized (ASP) lepton beams (having both longitudinal and transverse polarization components) also attract broad interests, because they can introduce three mutually orthogonal axes (required by fully reconstructing the density matrix of a spin-1/2 particle), modify effective BSM vertices [14, 20, 21], and thus play an unique role in future BSM experiments in e^+e^- colliders, e.g., rendering special spin structure functions as being observable in vector and axial-vector type BSM interactions [16], producing polarized top quark pairs as a probe of new physics [22, 23] and diagnosing spin and chirality structures of new particles in antler-topology processes [24].

In conventional methods, the transversely polarized lepton beams can be directly obtained in a storage ring via Sokolov-Ternov effect [25–29], which demands a long polarization time since large-size static magnetic fields are relatively weak (~Tesla), and the longitudinally polarized ones can be created via high-energy circularly polarized (CP) γ photons interacting with high-Z target [30–32] (Bethe-Heitler e^+e^- pair production process [33]), in which the low luminosity of γ photons requires a large amount of repetitions to yield a dense positron beam for further applications [34]. The transverse and longitudinal polarizations can be transformed to each other by a spin rotator, which demands quasi-monoenergetic beams with a risk of beam intensity reduction [35, 36].

Modern ultrashort ultraintense laser pulses [37–39] enable alternative efficient methods to generate dense polarized lepton beams in femtoseconds via nonlinear quantum electrodynamics (QED) processes [40], e.g. nonlinear Compton scattering [41–44] and Breit-Wheeler (BW) e^+e^- pair production [45–49]. As reported, the leptons can be greatly transversely polarized in a standing-wave [50–52], elliptically polarized (EP) [53], or bichromatic laser [54–56] but not in a monochromatic symmetric laser [57–59]. And, longitudinally polarized positrons can be produced by CP γ photons through the helicity transfer [60] (similar to the Bethe-Heitler process). Moreover, two-step schemes have also been proposed: low-energy polarized leptons are first generated by polarized photocathodes [61–63], polarized atoms [64] or molecular photodissociation [65–67], and then accelerated to ultrarelativistic energies via laser- [68, 69] or beam-driven [70, 71] plasma wakefield (conventional accelerators work as well). All those proposals provide leptons either greatly transversely or longitudinally polarized, however, how to generate above mentioned unique ASP lepton beams is still a great challenge.

In this Letter, the generation of ASP GeV lepton beams has been investigated in the interaction of polarized γ photons with a counter-propogating ultraintense linearly polarized (LP) asymmetric laser pulse [see the interaction scenario in Fig. 1].

* k.hatsagortsyan@mpi-hd.mpg.de

† jianxing@xjtu.edu.cn

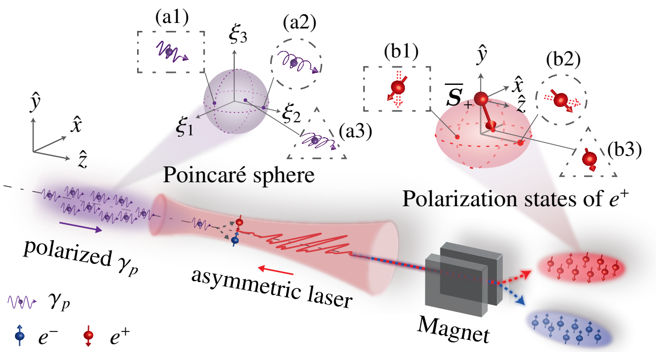

FIG. 1. Scenario of generation of ASP lepton beams via nonlinear BW process. A LP asymmetric laser pulse (propagating along $-\hat{z}$ direction and polarizing along $\hat{x}$ axis) head-on collides with polarized γ photons (γ_p) to create ASP electron and positron beams. (a1)-(a3) indicate LP, CP and EP γ photons, respectively, and (b1)-(b3) show average polarizations of created positrons $\overline{\boldsymbol{S}}_+$ corresponding to (a1)-(a3), respectively. The red-solid arrow and ellipsoid indicate the direction and amplitude of $\overline{\boldsymbol{S}}_+$, respectively. The red-dashed arrows in (b1) ($\parallel \hat{y}$) and (b2) ($\parallel \hat{z}$) indicate particular cases of neglecting the polarization of γ photons and employing symmetric laser field, respectively.

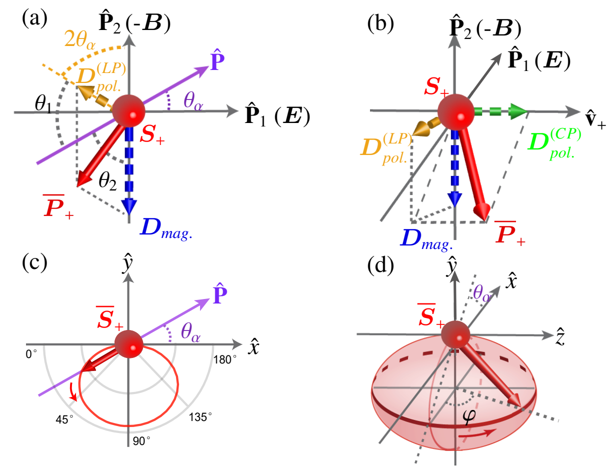

FIG. 2. (a) and (b): Polarization of sample positron $\boldsymbol{S}_+$ created by LP and EP γ photons, respectively. In our interaction scheme [see Fig. 1] we employ $\hat{\mathbf{P}}_1 = \hat{\boldsymbol{E}} \approx \hat{\mathbf{a}}_+$ and $\hat{\mathbf{P}}_2 = -\hat{\boldsymbol{B}} \approx \hat{\boldsymbol{b}}_+$. $\overline{\boldsymbol{P}}_+$ indicates the direction of the instantaneous SQA with two transverse components $\boldsymbol{D}_{mag}$, $\boldsymbol{D}_{pol}^{(LP)}$ and one longitudinal component $D_{pol}^{(CP)}$ [see Eq.(3)]. For LP γ photon in (a), $D_{pol}^{(CP)} = 0$ and θ_α indicates the polarization angle to $\hat{\mathbf{P}}_1$. θ_1 and θ_2 are the angles of $\hat{\mathbf{P}}$ to $\boldsymbol{D}_{pol.}^{(LP)}$ and $\boldsymbol{D}_{mag.}$, respectively. (c) and (d): Average polarization of positrons $\overline{\boldsymbol{S}}_+$ created by LP and EP γ photons, respectively. The red arrow and circle (ellipsoid) indicate the direction and amplitude of $\overline{\boldsymbol{S}}_+$ [see Eq. (4)], respectively.

We develop a fully spin-resolved semi-classical Monte Carlo algorithm to describe photon-polarization-dependent pair production and polarization in nonlinear BW process. We find that the polarization of created pairs is simultaneously determined by the polarization of parent γ photons, the polarization and asymmetry of scattering laser field, due to the spin angular momentum transfer and the asymmetric spin-dependent pair production probabilities, respectively [see details in Fig. 2 and Eq. (4)]. As employing unpolarized γ photons or ignoring the polarization of parent γ photons the pair polarization will rely on the laser polarization and asymmetry [see Fig. 1(b1)], and as employing a symmetric laser field the transverse polarization of the total beam will be suppressed (since the polarization directions in adjacent half laser cycles are opposite) and only the longitudinal polarization can be retained [see Fig. 1(b2)]. Our simulations show that dense GeV lepton beams with adjustable polarization degree up to about 80% can be obtained with currently achievable laser facilities to the benefit of many unique applications [see details in Fig. 3].

In strong laser field, a rich pair yield via nonlinear BW process requires the nonlinear QED parameter $\chi_\gamma \equiv |e|\sqrt{-(F_{\mu\nu}k_\gamma^\nu)^2}/m^3 \gtrsim 1$ [40, 72], and the created pairs may further emit photons via nonlinear Compton scattering, which is unnegligible as another nonlinear QED parameter $\chi_e \equiv |e|\sqrt{-(F_{\mu\nu}p^\nu)^2}/m^3 \gtrsim 1$ [40]. Here, e and m are the electron charge and mass, respectively, k_γ and p the 4-momenta of γ photon and positron (electron), respectively, and $F_{\mu\nu}$ the field tensor. Relativistic units with $c = \hbar = 1$ are used throughout. The photon polarization can be characterized by the unit vector $\hat{\mathbf{P}} = \cos(\theta_\alpha)\hat{\mathbf{P}}_1 + \sin(\theta_\alpha)\hat{\mathbf{P}}_2 \cdot e^{i\theta_\beta}$, and corresponding Stokes parameters are $(\xi_1, \xi_2, \xi_3) = [\sin(2\theta_\alpha)\cos(\theta_\beta), \sin(2\theta_\alpha)\sin(\theta_\beta), \cos(2\theta_\alpha)]$ [73, 74]. Here $\hat{\mathbf{P}}_1$ and $\hat{\mathbf{P}}_2$ are two orthogonal basis vectors, θ_α the polarization angle, θ_β the absolute phase, ξ_1 and ξ_3 describe the linear polarizations, and ξ_2 circular polarization. The fully spin-resolved pair production probability W_{pair} has been calculated via the QED operator method of Baier-Katkov-Fadin [75] in the local constant field approximation [40, 47, 72, 76–78] (valid at the invariant field parameter $a_0 = |e|E_0/m\omega \gg 1$, where E_0 and ω_0 are the laser field amplitude and frequency, respectively); see the complex expression of W_{pair} in [79].

Let's first summarize our methods of numerical simulation and analytical estimation. Note that in nonlinear BW process the polarization of electrons is similar with that of positrons, thus for simplicity we only discuss the case of positrons below. To study the positron polarization $\boldsymbol{S}_+$, we first sum over the electron polarization $\boldsymbol{S}_-$ in W_{pair}, and the probability relying on $\boldsymbol{S}_+$ is simplified as:

$$\frac{\mathrm{d}^2 W_{pair}^+}{\mathrm{d}\varepsilon_+ \mathrm{d}t} = W_0 (C + \boldsymbol{S}_+ \cdot \boldsymbol{D}), \tag{1}$$

where $W_0 = \alpha m^2 / \left(\sqrt{3}\pi\varepsilon_\gamma^2\right)$, $C = \mathrm{IntK}_{\frac{1}{3}}(\rho) + \frac{\varepsilon_-^2+\varepsilon_+^2}{\varepsilon_-\varepsilon_+}\mathrm{K}_{\frac{2}{3}}(\rho) - \xi_3 \mathrm{K}_{\frac{2}{3}}(\rho)$, $\boldsymbol{D} = \left(\xi_3 \frac{\varepsilon_\gamma}{\varepsilon_-} - \frac{\varepsilon_\gamma}{\varepsilon_+}\right)\mathrm{K}_{\frac{1}{3}}(\rho)\hat{\boldsymbol{b}}_+ - \xi_1 \frac{\varepsilon_\gamma}{\varepsilon_-}\mathrm{K}_{\frac{1}{3}}(\rho)\hat{\mathbf{a}}_+ + \xi_2\left[\frac{\varepsilon_+^2-\varepsilon_-^2}{\varepsilon_-\varepsilon_+}\mathrm{K}_{\frac{2}{3}}(\rho) + \frac{\varepsilon_\gamma}{\varepsilon_+}\mathrm{IntK}_{\frac{1}{3}}(\rho)\right]\hat{\mathbf{v}}_+$, $\hat{\boldsymbol{b}}_+ = \hat{\mathbf{v}}_+ \times \hat{\mathbf{a}}_+ \approx -\hat{\boldsymbol{k}}_\gamma \times \hat{\boldsymbol{E}} = -\hat{\boldsymbol{B}}$ is an unit vector anti-parallel to the magnetic field $\boldsymbol{B}$ (with direction vector $\hat{\boldsymbol{B}}$) in the rest frame of positron, $\boldsymbol{E}$ the electric field with direction vector $\hat{\boldsymbol{E}}$, $\hat{\mathbf{v}}_+$ and $\hat{\mathbf{a}}_+$ the unit vectors of the positron velocity and acceleration, respectively, $\rho = 2\varepsilon_\gamma^2 / \left(3\chi_\gamma\varepsilon_-\varepsilon_+\right)$, $\mathrm{IntK}_{\frac{1}{3}}(\rho) \equiv \int_\rho^\infty \mathrm{d}z \mathrm{K}_{\frac{1}{3}}(z)$, K_n the n-order modified Bessel function of the second kind, α the fine structure constant, ε_γ, ε_- and ε_+ the energies of parent γ photon, created electron and positron, respectively, with $\varepsilon_\gamma = \varepsilon_+ + \varepsilon_-$. When a γ photon decays into a pair, the positron spin state is collapsed into one of its basis states defined by the instantaneous spin quantization axis (SQA) along the energy-resolved average polarization vector [75]:

$$\mathrm{SQA} \parallel \overline{\boldsymbol{P}}_{+} = \boldsymbol{D}/C, \tag{2}$$

which can be rewritten as

$$\begin{aligned}\overline{\boldsymbol{P}}_{+} &= \left[\boldsymbol{D}_{mag.} + \boldsymbol{D}^{(LP)}_{pol.} + \boldsymbol{D}^{(CP)}_{pol.}\right]/C \\ &= \left[|\boldsymbol{D}_{mag.}|\hat{\boldsymbol{D}}_{mag.} + |\boldsymbol{D}^{(LP)}_{pol.}|\hat{\boldsymbol{D}}^{(LP)}_{pol.} + |\boldsymbol{D}^{(CP)}_{pol.}|\hat{\boldsymbol{D}}^{(CP)}_{pol.}\right]/C, \end{aligned}\tag{3}$$

where $\hat{\boldsymbol{D}}_{mag.} = -\hat{\mathbf{b}}_{+} \approx \hat{\boldsymbol{B}}$, $\hat{\boldsymbol{D}}^{(LP)}_{pol.} = \xi_3\hat{\boldsymbol{b}}_{+} - \xi_1\hat{\mathbf{a}}_{+}$ and $\hat{\boldsymbol{D}}^{(CP)}_{pol.} = \xi_2\hat{\mathbf{v}}_{+}$ rely on the magnetic field $\hat{\boldsymbol{B}}$, linear polarizations ξ_1 and ξ_3, and circular polarization ξ_2, respectively, with corresponding factors $|\boldsymbol{D}_{mag.}| = \frac{\varepsilon_\gamma}{\varepsilon_+}\mathrm{K}_{\frac{1}{3}}(\rho)$, $|\boldsymbol{D}^{(LP)}_{pol.}| = \frac{\varepsilon_\gamma}{\varepsilon_-}\mathrm{K}_{\frac{1}{3}}(\rho)$ and $|\boldsymbol{D}^{(CP)}_{pol.}| = \frac{\varepsilon_+^2-\varepsilon_-^2}{\varepsilon_-\varepsilon_+}\mathrm{K}_{\frac{2}{3}}(\rho) + \frac{\varepsilon_\gamma}{\varepsilon_+}\mathrm{IntK}_{\frac{1}{3}}(\rho)$, respectively. As the photon polarization is ignored, SQA $\parallel \hat{\boldsymbol{D}}_{mag.} \parallel \hat{\boldsymbol{B}}$, i.e., the positrons are polarized along the magnetic field $\boldsymbol{B}$ [56] [see Fig. 1(b1)]. The polarization geometries of positrons created by LP and EP γ photons are illustrated in Figs. 2(a) and (b), respectively. For LP γ photon, $\theta_\beta = 0$, $\hat{\boldsymbol{D}}^{(CP)}_{pol.} = 0$, $(\xi_1, \xi_2, \xi_3) = [\sin(2\theta_\alpha),\ 0,\ \cos(2\theta_\alpha)]$, and $\hat{\boldsymbol{D}}^{(LP)}_{pol.} = \xi_3\hat{\mathbf{b}}_{+} - \xi_1\hat{\mathbf{a}}_{+} = \cos(2\theta_\alpha)\hat{\mathbf{P}}_2 - \sin(2\theta_\alpha)\hat{\mathbf{P}}_1$. For general EP γ photon with $\xi_2 \neq 0$, the longitudinal polarization component must be taken into account.

For a positron beam, the average transverse polarizations $\overline{\boldsymbol{S}}_T$ in adjacent half laser cycles are opposite and cancel each other out due to the laser field oscillation, and consequently, $\overline{\boldsymbol{S}}_T$ is proportional to the asymmetry of the laser field, which can be characterized by the relative deviation between the pair production probabilities in positive and negative half cycles $\mathcal{A}_{field} = (W^{+,pos.}_{pair} - W^{+,neg.}_{pair})/(W^{+,pos.}_{pair} + W^{+,neg.}_{pair})$. Thus, one can estimate

$$\overline{\boldsymbol{S}}_{+} = \left\{\mathcal{A}_{field}\cdot\left[\overline{\boldsymbol{D}}_{mag.} + \overline{\boldsymbol{D}}^{(LP)}_{pol.}\right] + \overline{\boldsymbol{D}}^{(CP)}_{pol.}\right\}/\overline{C}, \tag{4}$$

where $\overline{\boldsymbol{D}}_{mag.} = \int_0^{\varepsilon_\gamma}\boldsymbol{D}_{mag.}\mathrm{d}\varepsilon_+$, $\overline{\boldsymbol{D}}^{(LP)}_{pol.} = \int_0^{\varepsilon_\gamma}\boldsymbol{D}^{(LP)}_{pol.}\mathrm{d}\varepsilon_+$, $\overline{\boldsymbol{D}}^{(CP)}_{pol.} = \int_0^{\varepsilon_\gamma}\boldsymbol{D}^{(CP)}_{pol.}\mathrm{d}\varepsilon_+$ and $\overline{C} = \int_0^{\varepsilon_\gamma}C\mathrm{d}\varepsilon_+$. For LP γ photons, $|\overline{\boldsymbol{D}}_{mag.}| = |\overline{\boldsymbol{D}}^{(LP)}_{pol.}|$ with $\theta_1 = \theta_2$ results in $\overline{\boldsymbol{S}}_{+} \parallel -\hat{\mathbf{P}}$ [see Fig. 2(c)]; for more general EP ones, as θ_β increases, $\overline{\boldsymbol{S}}_{+}$ will rotate anticlockwise by an azimuth angle φ, which can be calculated by Eq. (4) [see Fig. 2(d)]. $\overline{\boldsymbol{S}}_T = \mathcal{A}_{field}\mathcal{A}_{pol.}$ is dominated by $\mathcal{A}_{field}$ with $\mathcal{A}_{pol.} = \left|\overline{\boldsymbol{D}}_{mag.} + \overline{\boldsymbol{D}}^{(LP)}_{pol.}\right|/\overline{C}$ [see Fig. 4(a)], while the average longitudinal polarization $\overline{\boldsymbol{S}}_L$ is solely determined by $\overline{\boldsymbol{D}}^{(CP)}_{pol.}/\overline{C} \propto \xi_2$ as expected. In symmetric laser field with $\mathcal{A}_{field} = 0$, $\overline{\boldsymbol{S}}_T$ is very little and only $\overline{\boldsymbol{S}}_L$ can be obtained by employing longitudinally polarized γ photons ($\xi_2 \neq 0$) [60] [see Fig. 1(b2)]. The momentum and spin dynamics of the pairs propagating through the laser field are calculated following a Monte Carlo algorithm [49], including the radiative depolarization effects and spin procession [80–82]. See more details of our simulation method in [79].

Then, we illustrate typical results of created ASP positron beams in Fig 3. The employed laser and γ photon parameters

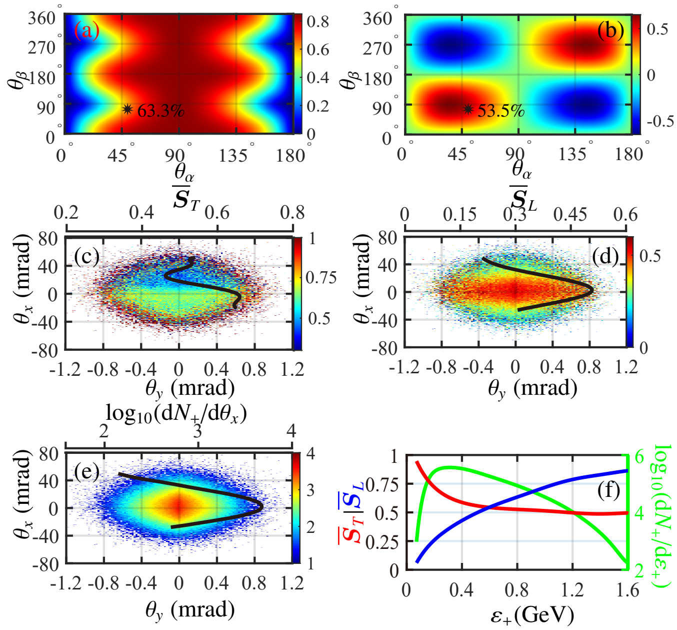

FIG. 3. (a) and (b): $\overline{\boldsymbol{S}}_T$ and $\overline{\boldsymbol{S}}_L$ of positrons with respect to θ_α and θ_β, respectively, analytically estimated by Eq. (4) with $\mathcal{A}_{field} = 0.8378$. The black points correspond to ($\theta_\alpha = 50°$, $\theta_\beta = 70°$). (c)-(f) are the numerical simulation results with ($\theta_\alpha = 50°$, $\theta_\beta = 70°$). (c)-(e): $\overline{\boldsymbol{S}}_T$, $\overline{\boldsymbol{S}}_L$ and the angle-resolved positron density $\log_{10}(\mathrm{d}^2N_+/\mathrm{d}\theta_x\mathrm{d}\theta_y)$ (rad^{-2}) with respect to the deflection angles $\theta_x = \arctan(p_{+,x}/p_{+,z})$ and $\theta_y = \arctan(p_{+,y}/p_{+,z})$, respectively. The black curves indicate $\overline{\boldsymbol{S}}_T$, $\overline{\boldsymbol{S}}_L$ and $\log_{10}(\mathrm{d}N_+/\mathrm{d}\theta_x)$ (mrad^{-1}) summing over θ_y vs θ_x, respectively. (f) $\overline{\boldsymbol{S}}_T$ (red), $\overline{\boldsymbol{S}}_L$ (blue) and the energy-resolved positron density $\log_{10}(\mathrm{d}N_+/\mathrm{d}\varepsilon_+)$ (GeV^{-1}) (green) vs ε_+. Other parameters are given in the text.

are as follows. A tightly focused LP bichromatic Gaussian laser pulse [79, 83] (a frequency-chirped laser pulse [84] can work similarly) propagates along $-\hat{z}$ direction and polarizes along $\hat{x}$ axis [see Fig. 1], with a phase difference $\Delta\phi = \pi/2$ to obtain the maximal field asymmetry, peak intensity $I_0 \approx 1.11\times10^{22}$ W/cm^2 (corresponding invariant field parameters $a_1 = 60$ and $a_2 = 15$), wavelengths $\lambda_1 = 2\lambda_2 = 1\mu$m, pulse durations $\tau_1 = \tau_2 = 15T_1$ with periods $T_1 = 2T_2$, and focal radii $w_1 = w_2 = 5\mu$m. This kind of laser pulse is currently feasible in petawatt laser facilities [37–39]. While, a cylindrical polarized γ photon beam propagates along $\hat{z}$ direction, with an initial energy $\varepsilon_\gamma = 1.8$GeV, energy spread $\Delta\varepsilon_\gamma/\varepsilon_\gamma = 0.06$, angular divergence $\Delta\theta_\gamma = 0.3$mrad, beam radius $w_\gamma = 1\mu$m, beam length $L_\gamma = 5\mu$m, photon number $N_\gamma = 10^6$ and density $n_\gamma \approx 6.37\times10^{16}$cm^{-3} having a transversely Gaussian and longitudinally uniform distribution. Such a γ photon beam may be generated via synchrotron radiation [31, 85], bremsstrahlung [86], linear [30] or nonlinear Compton scattering [87–89]. The pair production is remarkable at these parameters since $\overline{\chi}_\gamma \approx 0.96$.

According to Eq. (4), the polarizations of created positron beam ($\overline{\boldsymbol{S}}_T$ and $\overline{\boldsymbol{S}}_L$) can be controlled by adjusting the polarization of parent γ photons (θ_α and θ_β) [see Figs. 3(a) and (b)], which indicates the spin angular momentum transfer

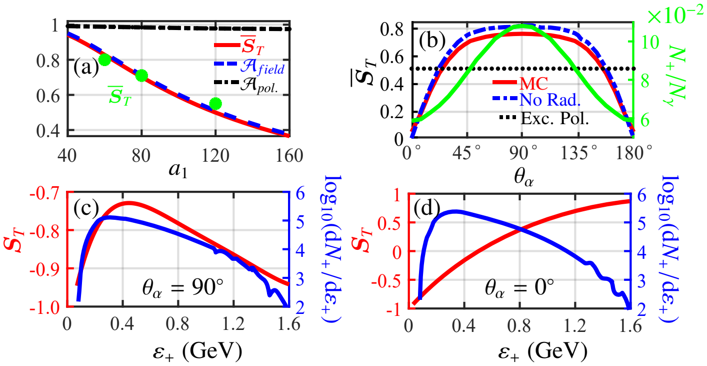

FIG. 4. (a) $\mathcal{A}_{pol.}$ (black-dash-dotted), $\mathcal{A}_{field}$ (blue-dashed) and $\overline{\boldsymbol{S}}_T$ (red-solid) analytically calculated by Eq. (4) vs a_1 ($a_2 = a_1/4$), and the green points $\overline{\boldsymbol{S}}_T$ are our numerical results. $\theta_\alpha = 90°$. At $a_1 = 60$, 80 and 120, respectively, the corresponding $\overline{\chi}_\gamma \approx 0.96$, 1.20 and 1.63, respectively. (b) $\overline{\boldsymbol{S}}_T$ and the yield ratio of positrons N_+/N_γ (green-solid) vs θ_α. The red-solid, blue-dash-dotted and black-dotted curves indicate the results of $\overline{\boldsymbol{S}}_T$ calculated by our Monte Carlo method, artificially ignoring the radiative depolarization effects of the positrons propagating through the laser field, and excluding the polarization effects of parent γ photons in nonlinear BW process, respectively. (c) and (d): $\boldsymbol{S}_T$ (red-solid) and $\log_{10}(\mathrm{d}N_+/\mathrm{d}\varepsilon_+)(\mathrm{GeV}^{-1})$ (blue) vs ε_+ at $\theta_\alpha = 90°$ and $\theta_\alpha = 0°$, respectively. Here $\theta_\beta = 0°$, and other parameters are the same as those in Fig. 3.

from parent γ photons to created pairs. $\overline{\boldsymbol{S}}_T \propto \sqrt{\xi_1^2 + \xi_3^2} = \sqrt{\sin^2(2\theta_\alpha)\cos^2(\theta_\beta) + \cos^2(2\theta_\alpha)}$ is mainly determined by θ_α and can reach above 80%, while $\overline{\boldsymbol{S}}_L \propto \xi_2 = \sin(2\theta_\alpha)\sin(\theta_\beta)$ periodically varies with respect to θ_α and θ_β and its amplitude can achieve about 60%. For a specific case with $\theta_\alpha = 50°$ and $\theta_\beta = 70°$, the analytical estimations are $\overline{\boldsymbol{S}}_T \approx 63.3\%$ and $\overline{\boldsymbol{S}}_L \approx 53.5\%$ [see the black-star points in Figs. 3(a) and (b)], and corresponding numerical results are $\overline{\boldsymbol{S}}_T \approx 62.1\%$ and $\overline{\boldsymbol{S}}_L \approx 50.3\%$ [79]. The little deviations are derived from that in analytical estimations we employ a constant $\mathcal{A}_{field}$, which actually has spatial and temporal profiles in our numerical simulations. As the created positrons propagate through the laser field, the average polarizations slightly decrease to $\overline{\boldsymbol{S}}_T \approx 59.4\%$ and $\overline{\boldsymbol{S}}_L \approx 44.8\%$ [see Figs. 3(c) and (d)] due to the quantum radiative depolarization effects [53] [see [79] and Fig. 4(b)]. $\overline{\boldsymbol{S}}_T \propto \mathcal{A}_{field}$ is asymmetric in angular distribution due to asymmetric $\mathcal{A}_{field}$, which doesn't affect the symmetry of $\overline{\boldsymbol{S}}_L \propto \xi_2$. The yield rate of positrons $N_+/N_\gamma \approx 0.1$ is much higher than that of the common method employing Bethe-Heitler pair production ($\sim 10^{-3} - 10^{-4}$) [30–32], since $N_+ \sim \alpha a_0$ is rather large in ultraintense laser field [40, 75]; see Fig. 3(e). The flux of the positron beam is approximately 3.0×10^{19}/s with duration $\tau_+ \approx \tau_\gamma$ (due to the relativistic effect). The emittance $\epsilon \approx w_+\theta_{div.} \sim 10^{-2}$ mm·mrad fulfills the experimental requirements of the beam injectors [90], with radius $w_+ \approx w_\gamma = 1\mu$m and angular divergence $\theta_{div.} \sim 30$mrad [FWHM in Fig. 3(e)]. Due to the stochastic effects of the pair production and further radiation, the energy of the positron beam spreads with a density peak at $\varepsilon_+ \approx 0.3$GeV [see Fig. 3(f)]. With the increase of ε_+, $\overline{\boldsymbol{S}}_T$ ($\overline{\boldsymbol{S}}_L$) monotonically decreases (increases) from above 90% (0%) to about 50% (above 85%), since the pair polarization is mainly determined by the polarization of the laser (parent γ photons) at low (high) ε_+ (see [79]). For $\varepsilon_+ = 0.4$GeV, 0.8GeV and 1.2GeV, respectively, corresponding $\overline{\boldsymbol{S}}_T$ ($\overline{\boldsymbol{S}}_L$) is about 58.7%, 52.6% and 49.8% (42.6%, 63.4% and 78.8%), respectively, and brilliance about 4.6×10^{20}, 1.4×10^{20} and 0.5×10^{20} positrons/(s mm^2 mrad^2 0.1% BW), respectively, with angular divergence (FWHM) of about 24.9 mrad^2, 15.9 mrad^2 and 13.0 mrad^2, respectively.

We underline that as the ultra-relativistic laser intensity $a_0(\sim a_1) \propto \chi_\gamma$ continuously increases, $W_{pair}^{+,pos.}$ and $W_{pair}^{+,neg.}$ are both gradually approaching the saturation threshold, and thus $\overline{\boldsymbol{S}}_T \propto \mathcal{A}_{field}$ decreases continuously [see Fig. 4(a)]. As employing unpolarized γ photons or artificially ignoring the polarization effects of γ photons in nonlinear BW process, for given parameters $\overline{\boldsymbol{S}}_T$ is only about 50.8%, however, employing polarized γ photons $\overline{\boldsymbol{S}}_T$ can achieve up to 76.2% with a peak yield rate $N_+/N_\gamma \approx 0.11$ at $\theta_\alpha = 90°$. And in a broad range of $45° \lesssim \theta_\alpha \lesssim 135°$ one can obtain $\overline{\boldsymbol{S}}_T \gtrsim 60\%$ with $N_+/N_\gamma \gtrsim 0.08$ [see Fig. 4(b)]. The energy-resolved $\overline{\boldsymbol{S}}_T$ and densities at $\theta_\alpha = 90°$ and 0° are represented in Figs. 4(c) and (d), respectively. It's interesting that at $\theta_\alpha = 0°$ even though $\overline{\boldsymbol{S}}_T$ is very little, highly polarized positron beams can still be obtained by energy choosing by magnets.

For experimental feasibility, the impact of the laser and γ photon parameters (e.g., the laser intensity, pulse duration, colliding angle, and the angular spreading, energy and energy spreading of the γ photon beam) on the positron polarization is investigated, and the results keep uniform (see [79]). Moreover, for a more general case: an electron beam head-on collides with a LP bichromatic laser pulse to generate positrons, the positrons are only weakly transversely polarized, since the polarization of intermediate γ photons is nearly parallel to that of the laser field [79].

In conclusion, we reveal the fully spin-resolved pair polarization mechanism in nonlinear BW process, which can be observed by the average polarization vector in an asymmetric (e.g. well known bichromatic and frequency-chirped) laser field. And we put forward an efficient method to generate dense ASP GeV lepton beams with the polarization degree up to about 80% with currently achieveable petawatt laser facilities [37–39], which have unique applications for high-energy physics and particle physics, in particular, as injectors of the polarized e^+e^- colliders for searching for BSM new physics [4, 13–16, 19–24, 93].

Acknowledgement: This work is supported by the National Natural Science Foundation of China (Grants Nos. 12022506, 11874295, 11875219 and 11905169), and the National Key R&D Program of China (Grant No. 2018YFA0404801).

[1] J. F. C. Wardle, D. C. Homan, R. Ojha, and D. H. Roberts, "Electron-positron jets associated with the quasar 3c279," Nature , 457–461 (1998).

[2] Igor Žutić, Jaroslav Fabian, and S. Das Sarma, "Spintronics: Fundamentals and applications," Rev. Mod. Phys. **76**, 323–410 (2004).

[3] M. Achasov M.N. et al. The BESIII Collaboration., Ablikim (BES), "Polarization and Entanglement in Baryon-Antibaryon Pair Production in Electron-Positron Annihilation," Nat. Phys. **15**, 631–634 (2019).

[4] G. Moortgat-Pick, T. Abe, G. Alexander, B. Ananthanarayan, A.A. Babich, V. Bharadwaj, D. Barber, A. Bartl, A. Brachmann, S. Chen, J. Clarke, J.E. Clendenin, J. Dainton, K. Desch, M. Diehl, B. Dobos, T. Dorland, H.K. Dreiner, H. Eberl, J. Ellis, K. Flöttmann, H. Fraas, F. Franco-Sollova, F. Franke, A. Freitas, J. Goodson, J. Gray, A. Han, S. Heinemeyer, S. Hesselbach, T. Hirose, K. Hohenwarter-Sodek, A. Juste, J. Kalinowski, T. Kernreiter, O. Kittel, S. Kraml, U. Langenfeld, W. Majerotto, A. Martinez, H.-U. Martyn, A. Mikhailichenko, C. Milstene, W. Menges, N. Meyners, K. Mönig, K. Moffeit, S. Moretti, O. Nachtmann, F. Nagel, T. Nakanishi, U. Nauenberg, H. Nowak, T. Omori, P. Osland, A.A. Pankov, N. Paver, R. Pitthan, R. Pöschl, W. Porod, J. Proulx, P. Richardson, S. Riemann, S.D. Rindani, T.G. Rizzo, A. Schälicke, P. Schüler, C. Schwanenberger, D. Scott, J. Sheppard, R.K. Singh, A. Sopczak, H. Spiesberger, A. Stahl, H. Steiner, A. Wagner, A.M. Weber, G. Weiglein, G.W. Wilson, M. Woods, P. Zerwas, J. Zhang, and F. Zomer, "Polarized positrons and electrons at the linear collider," Phys. Rep. **460**, 131 – 243 (2008).

[5] Howard Bear, Tim Barklow, Keisuke Fujii, Yuanning Gao, Andre Hoang, Shinya Kanemura, Jenny List, Heather E. Logan, Andrei Nomerotski, Maxim Perelstein, Michael E. Peskin, Roman Pōschl, Jürgen Reuter, Sabine Riemann, Aurore Savoy-Navarro, Geraldine Servant, Tim M. P. Tait, and Jaehoon Yu, "The international linear collider technical design report - volume 2: Physics," (2013), arXiv:1306.6352 [hep-ph].

[6] Aysegul Usun Simitcioglu, Ilhan Tapan, R. Tomas, J. Barranco, and M. Beckmann, "Beam offset impact on the polarization in the clic beam delivery system," Can. J. Phys. **96**, 1266–1271 (2018).

[7] V. Ari, A.A. Billur, S.C. İnan, and M. Köksal, "Anomalous $ww\gamma$ couplings with beam polarization at the compact linear collider," Nucl. Phys. B **906**, 211 – 230 (2016).

[8] Zhe Duan, Jie Gao, Xiaoping Li, Dou Wang, Yiwei Wang, Wenhao Xia, Qingjin Xu, Chenghui Yu, and Yuan Zhang, "Concepts of longitudinally polarized electron and positron colliding beams in the circular electron positron collider," in *10th International Particle Accelerator Conference* (2019) p. MOPMP012.

[9] Sergei Nikitin, "Polarization issues in circular electron positron super-colliders," Int. J. Mod. Phys. A **35**, 2041001 (2020).

[10] M. Diehl, O. Nachtmann, and F. Nagel, "Probing triple gauge couplings with transverse beam polarisation in e +e- → W+W-," Eur. Phys. J. C **32**, 17–27 (2003).

[11] Dhiman Chakraborty, Jacobo Konigsberg, and David Rainwater, "Top-quark physics," Annu. Rev. Nucl. Part. Sci. **53**, 301–351 (2003).

[12] Alfred Bartl, Karl Hohenwarter-Sodek, Thomas Kernreiter, and Olaf Kittel, "Cp asymmetries with longitudinal and transverse beam polarizations in neutralino production and decay into the z^0 boson at the ilc," J. High Energy Phys. **2007**, 079–079 (2007).

[13] Peter Herczeg, "Cp-violating electron-nucleon interactions from leptoquark exchange," Phys. Rev. D **68**, 116004 (2003).

[14] B. Ananthanarayan and Saurabh D. Rindani, "CP violation at a linear collider with transverse polarization," Phys. Rev. D **70**, 036005 (2004).

[15] B. Ananthanarayan and Saurabh D. Rindani, "Transverse beam polarization and cp violation in $e^+e^- \to \gamma z$ with contact interactions," Phys. Lett. B **606**, 107–115 (2005).

[16] B. Ananthanarayan and Saurabh D. Rindani, "Inclusive spin-momentum analysis and new physics at a polarized electron-positron collider," Eur. Phys. J. C **78**, 1–17 (2018).

[17] J. Fleischer, K. Kołodziej, and F. Jegerlehner, "Transverse versus longitudinal polarization effects in e+e- → +W-," Phys. Rev. D **49**, 2174–2187 (1994).

[18] Ken-ichi Hikasa, "Transverse-polarization effects in e^+e^- collisions: The role of chiral symmetry," Phys. Rev. D **33**, 3203–3223 (1986).

[19] Thomas G. Rizzo, "Transverse polarization signatures of extra dimensions at linear colliders," J. High Energy Phys. **7**, 157–172 (2003).

[20] G.V. Dass and G.G. Ross, "Neutral and weak currents in e^+e^- annihilation to hadrons," Nucl. Phys. B **118**, 284–310 (1977).

[21] C. P. Burgess and J. A. Robinson, "Transverse polarization at e^+e^- colliders and CP violation from new physics," Int. J. Mod. Phys. A **6**, 2707–2728 (1991).

[22] R. Harlander, M. Jeżabek, J. H. Kühn, and M. Peter, "Top quark polarization in polarized e^+e^- annihilation near threshold," Z. Phys. C: Part. Fields **73**, 477–494 (1997).

[23] Rohini M Godbole, Saurabh D Rindani, and Ritesh K Singh, "Lepton distribution as a probe of new physics in production and decay of thetquark and its polarization," J. High Energy Phys. **2006**, 021–021 (2006).

[24] S. Y. Choi, N. D. Christensen, D. Salmon, and X. Wang, "Spin and chirality effects in antler-topology processes at high energy e^+e^- colliders," Eur. Phys. J. C **75**, 481 (2015).

[25] A. A. Sokolov and I. M. Ternov, "On polarization and spin effects in the theory of synchrotron radiation," Sov. Phys. Dokl. **8**, 1203 (1964).

[26] A. A. Sokolov and I. M. Ternov, *Synchrotron Radiation* (Akademic, Germany, 1968).

[27] V. N. Baier and V. M. Katkov, "Radiational polarization of electrons in inhomogeneous magnetic field," Phys. Lett. A **24**, 327–329 (1967).

[28] V. N. Baier, "Radiative polarization of electron in storage rings," Sov. Phys. Usp. **14**, 695 (1972).

[29] Y. Derbenev and A. M. Kondratenko, "Polarization kinematics of particles in storage rings," Sov. Phys. JETP **37**, 968 (1973).

[30] T. Omori, M. Fukuda, T. Hirose, Y. Kurihara, R. Kuroda, M. Nomura, A. Ohashi, T. Okugi, K. Sakaue, T. Saito, J. Urakawa, M. Washio, and I. Yamazaki, "Efficient propagation of polarization from laser photons to positrons through compton scattering and electron-positron pair creation," Phys. Rev. Lett. **96**, 114801 (2006).

[31] G. Alexander, J. Barley, Y. Batygin, S. Berridge, V. Bharadwaj, G. Bower, W. Bugg, F.-J. Decker, R. Dollan, Y. Efremenko, V. Gharibyan, C. Hast, R. Iverson, H. Kolanoski, J. Kovermann, K. Laihem, T. Lohse, K. T. McDonald, A. A. Mikhailichenko, G. A. Moortgat-Pick, P. Pahl, R. Pitthan, R. Pöschl, E. Reinherz-Aronis, S. Riemann, A. Schälicke, K. P. Schüler, T. Schweizer, D. Scott, J. C. Sheppard, A. Stahl, Z. M. Szalata, D. Walz, and A. W. Weidemann, "Observation of polarized positrons from an undulator-based source," Phys. Rev. Lett. **100**, 210801 (2008).

[32] D. Abbott, P. Adderley, A. Adeyemi, P. Aguilera, M. Ali, *et al.* (PEPPo Collaboration), "Production of highly polarized positrons using polarized electrons at mev energies," Phys. Rev. Lett. **116**, 214801 (2016).

[33] W. Heitler, *The Quantum Theory of Radiation* (Clarendon Press, Oxford, 1954).

[34] A. Variola, "Advanced positron sources," Nucl. Instr. Meth. Phys. Res. A **740**, 21–26 (2014).

[35] Jean Buon and Klaus Steffen, "Hera variable-energy "mini" spin rotator and head-on ep collision scheme with choice of electron helicity," Nucl. Instrum. Methods Phys. Res., Sect. A **245**, 248–261 (1986).

[36] K. Moffeit, M. Woods, P. Schüler, K. Mönig, and P. Bambade, "Spin rotation schemes at the ilc for two interaction regions and positron polarization with both helicities," SLAC-TN-05-045, LCC-0159, IPBI-TN-2005-2 (2005).

[37] Jin Woo Yoon, Cheonha Jeon, Junghoon Shin, Seong Ku Lee, Hwang Woon Lee, Il Woo Choi, Hyung Taek Kim, Jae Hee Sung, and Chang Hee Nam, "Achieving the laser intensity of 5.5×10^{22} w/cm^2 with a wavefront-corrected multi-pw laser," Opt. Express **27**, 20412–20420 (2019).

[38] Colin N. Danson, Constantin Haefner, Jake Bromage, Thomas Butcher, Jean-Christophe F. Chanteloup, Enam A. Chowdhury, Almantas Galvanauskas, Leonida A. Gizzi, Joachim Hein, David I. Hillier, and et al., "Petawatt and exawatt class lasers worldwide," High Power Laser Sci. Eng. **7**, e54 (2019).

[39] S. Gales, K. A. Tanaka, D. L. Balabanski, F. Negoita, D. Stutman, O. Tesileanu, C. A. Ur, D. Ursescu, I. An-drei, S. Ataman, M. O. Cernaianu, L. DAlessi, I. Dancus, B. Diaconescu, N. Djourelov, D. Filipescu, P. Ghenuche, D. G. Ghita, C. Matei, K. Seto, M. Zeng, and N. V. Zamfir, "The extreme light infrastructure nuclear physics (eli-np) facility: new horizons in physics with 10 pw ultra-intense lasers and 20 mev brilliant gamma beams," Rep. Prog. Phys. **81**, 094301 (2018).

[40] V. I. Ritus, "Quantum effects of the interaction of elementary particles with an intense electromagnetic field," J. Sov. Laser Res. **6**, 497 (1985).

[41] I. I. Goldman, "Intensity effects in compton scattering," Sov. Phys. JETP **19**, 954 (1964), [Zh. Eksp. Teor. Fiz. 46, 1412 (1964)].

[42] A. I. Nikishov and V. I. Ritus, "Quantum processes in the field of a plane electromagnetic wave and in a constant field. i," Sov. Phys. JETP **19**, 529 (1964), [Zh. Eksp. Teor. Fiz. 46, 776 (1964)].

[43] Lowell S. Brown and T. W. B. Kibble, "Interaction of intense laser beams with electrons," Phys. Rev. **133**, A705–A719 (1964).

[44] K. Yokoya, CAIN2.42 Users Manual., `https://ilc.kek.jp/~yokoya/CAIN/Cain242/`.

[45] Howard R. Reiss, "Absorption of light by light," J. Math. Phys. **3**, 59–67 (1962).

[46] D. Y. Ivanov, G. L. Kotkin, and V. G. Serbo, "Complete description of polarization effects in e^+e^- pair production by a photon in the field of a strong laser wave," Eur. Phys. J. C **40**, 27 (2005).

[47] D. Seipt and B. King, "Spin- and polarization-dependent locally-constant-field-approximation rates for nonlinear Compton and Breit-Wheeler processes," Phys. Rev. A **102**, 052805 (2020).

[48] Tobias N. Wistisen, "Numerical approach to the semiclassical method of pair production for arbitrary spins and photon polarization," Phys. Rev. D **101**, 076017 (2020).

[49] Feng Wan, Yu Wang, Ren-Tong Guo, Yue-Yue Chen, Rashid Shaisultanov, Zhong-Feng Xu, Karen Z. Hatsagortsyan, Christoph H. Keitel, and Jian-Xing Li, "High-energy γ-photon polarization in nonlinear Breit-Wheeler pair production and γ polarimetry," Phys. Rev. Research **2**, 032049 (2020).

[50] D. Del Sorbo, D. Seipt, T. G. Blackburn, A. G. R. Thomas, C. D. Murphy, J. G. Kirk, and C. P. Ridgers, "Spin polarization of electrons by ultraintense lasers," Phys. Rev. A **96**, 043407 (2017).

[51] D. Del Sorbo, D. Seipt, A. G. R. Thomas, and C. P. Ridgers, "Electron spin polarization in realistic trajectories around the magnetic node of two counter-propagating, circularly polarized, ultra-intense lasers," Plasma Phys. Control. Fusion **60**, 064003 (2018).

[52] D. Seipt, D. Del Sorbo, C. P. Ridgers, and A. G. R. Thomas, "Theory of radiative electron polarization in strong laser fields," Phys. Rev. A **98**, 023417 (2018).

[53] Yan-Fei Li, Rashid Shaisultanov, Karen Z. Hatsagortsyan, Feng Wan, Christoph H. Keitel, and Jian-Xing Li, "Ultrarelativistic electron-beam polarization in single-shot interaction with an ultraintense laser pulse," Phys. Rev. Lett. **122**, 154801 (2019).

[54] Daniel Seipt, Dario Del Sorbo, Christopher P. Ridgers, and Alec G. R. Thomas, "Ultrafast polarization of an electron beam in an intense bichromatic laser field," Phys. Rev. A **100**, 061402(R) (2019).

[55] Huai-Hang Song, Wei-Min Wang, Jian-Xing Li, Yan-Fei Li, and Yu-Tong Li, "Spin-polarization effects of an ultrarelativistic electron beam in an ultraintense two-color laser pulse," Phys. Rev. A **100**, 033407 (2019).

[56] Yue-Yue Chen, Pei-Lun He, Rashid Shaisultanov, Karen Z. Hatsagortsyan, and Christoph H. Keitel, "Polarized positron beams via intense two-color laser pulses," Phys. Rev. Lett. **123**, 174801 (2019).

[57] G. L. Kotkin, V. G. Serbo, and V. I. Telnov, "Electron (positron) beam polarization by compton scattering on circularly polarized laser photons," Phys. Rev. ST Accel. Beams **6**, 011001 (2003).

[58] D. Yu. Ivanov, G. L. Kotkin, and V. G. Serbo, "Complete description of polarization effects in emission of a photon by an electron in the field of a strong laser wave," Eur. Phys. J. C **36**, 127–145 (2004).

[59] Dmitry V. Karlovets, "Radiative polarization of electrons in a strong laser wave," Phys. Rev. A **84**, 062116 (2011).

[60] Yan-Fei Li, Yue-Yue Chen, Wei-Min Wang, and Hua-Si Hu, "Production of highly polarized positron beams via helicity transfer from polarized electrons in a strong laser field," Phys. Rev. Lett. **125**, 044802 (2020).

[61] D. T. Pierce, R. J. Celotta, G.-C. Wang, W. N. Unertl, A. Galejs, C. E. Kuyatt, and S. R. Mielczarek, "The GaAs spin polarized electron source," Rev. Sci. Instrum. **51**, 478–499 (1980).

[62] M. Kuwahara, S. Kusunoki, X. G. Jin, T. Nakanishi, Y. Takeda, K. Saitoh, T. Ujihara, H. Asano, and N. Tanaka, "30-kV spin-polarized transmission electron microscope with GaAs-GaAsP strained superlattice photocathode," Appl. Phys. Lett. **101**, 033102 (2012).

[63] P. W. Zitzewitz, J. C. Van House, A. Rich, and D. W. Gidley, "Spin polarization of low-energy positron beams," Phys. Rev. Lett. **43**, 1281–1284 (1979).

[64] Ingo Barth and Olga Smirnova, "Spin-polarized electrons produced by strong-field ionization," Phys. Rev. A **88**, 013401 (2013).

[65] T. P. Rakitzis, P. C. Samartzis, R. L. Toomes, T. N. Kitsopoulos, Alex Brown, G. G. Balint-Kurti, O. S. Vasyutinskii, and J. A. Beswick, "Spin-Polarized Hydrogen Atoms from Molecular Photodissociation," Science **300**, 1936–1938 (2003).

[66] Dimitris Sofikitis, Pavle Glodic, Greta Koumarianou, Hongyan Jiang, Lykourgos Bougas, Peter C. Samartzis, Alexander Andreev, and T. Peter Rakitzis, "Highly nuclear-spin-polarized deuterium atoms from the uv photodissociation of deuterium iodide," Phys. Rev. Lett. **118**, 233401 (2017).

[67] Dimitris Sofikitis, Chrysovalantis S. Kannis, Gregoris K. Boulo-

giannis, and T. Peter Rakitzis, "Ultrahigh-density spin-polarized h and d observed via magnetization quantum beats," Phys. Rev. Lett. **121**, 083001 (2018).
[68] Meng Wen, Matteo Tamburini, and Christoph H. Keitel, "Polarized laser-wakefield-accelerated kiloampere electron beams," Phys. Rev. Lett. **122**, 214801 (2019).
[69] Yitong Wu, Liangliang Ji, Xuesong Geng, Qin Yu, Nengwen Wang, Bo Feng, Zhao Guo, Weiqing Wang, Chengyu Qin, Xue Yan, Lingang Zhang, Johannes Thomas, Anna Hützen, Markus Büscher, T Peter Rakitzis, Alexander Pukhov, Baifei Shen, and Ruxin Li, "Polarized electron-beam acceleration driven by vortex laser pulses," New Journal of Physics **21**, 073052 (2019).
[70] Yitong Wu, Liangliang Ji, Xuesong Geng, Qin Yu, Nengwen Wang, Bo Feng, Zhao Guo, Weiqing Wang, Chengyu Qin, Xue Yan, Lingang Zhang, Johannes Thomas, Anna Hützen, Alexander Pukhov, Markus Büscher, Baifei Shen, and Ruxin Li, "Polarized electron acceleration in beam-driven plasma wakefield based on density down-ramp injection," Phys. Rev. E **100**, 043202 (2019).
[71] Zan Nie, Fei Li, Felipe Morales, Serguei Patchkovskii, Olga Smirnova, Weiming An, Noa Nambu, Daniel Matteo, Kenneth A. Marsh, Frank Tsung, Warren B. Mori, and Chan Joshi, " In Situ Generation of High-Energy Spin-Polarized Electrons in a Beam-Driven Plasma Wakefield Accelerator ," Physical Review Letters **126**, 54801 (2021), 2101.10378.
[72] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals* (World Scientific, Singapore, 1998).
[73] William H. McMaster, "Matrix representation of polarization," Rev. Mod. Phys. **33**, 8–28 (1961).
[74] O.M. Boyarkin, *Advanced particle physics volume I: Particles, fields, and quantum electrodynamics* (2011).
[75] V. N. Baier, V. M. Katkov, and V. S. Fadin, *Radiation from relativistic electrons* (Atomizdat, Moscow, 1973).
[76] A. Di Piazza, M. Tamburini, S. Meuren, and C. H. Keitel, "Implementing nonlinear compton scattering beyond the local-constant-field approximation," Phys. Rev. A **98**, 012134 (2018).
[77] A. Ilderton, "Note on the conjectured breakdown of qed perturbation theory in strong fields," Phys. Rev. D **99**, 085002 (2019).
[78] A. Di Piazza, M. Tamburini, S. Meuren, and C. H. Keitel, "Improved local-constant-field approximation for strong-field qed codes," Phys. Rev. A **99**, 022125 (2019).
[79] See Supplemental Material for details on the employed laser fields, the applied simulation methods, and the simulation results for other laser or γ photon parameters.
[80] L. H. Thomas, "The motion of the spinning electron," Nature (London) **117**, 514 (1926).
[81] L. H. Thomas, "The kinematics of an electron with an axis," Philos. Mag. **3**, 1–22 (1927).
[82] V. Bargmann, Louis Michel, and V. L. Telegdi, "Precession of the polarization of particles moving in a homogeneous electromagnetic field," Phys. Rev. Lett. **2**, 435–436 (1959).
[83] Yousef I. Salamin and Christoph H. Keitel, "Electron acceleration by a tightly focused laser beam," Phys. Rev. Lett. **88**, 095005 (2002).
[84] Benjamin J. Galow, Yousef I. Salamin, Tatyana V. Liseykina, Zoltán Harman, and Christoph H. Keitel, "Dense monoenergetic proton beams from chirped laser-plasma interaction," Phys. Rev. Lett. **107**, 185002 (2011).
[85] D. E. Baynham, Y. Ivanyushenkov, J. A. Clarke, A. Brummitt, V. Bayliss, T. Bradshaw, D. J. Scott, J. Rochford, S. Carr, G. Burton, O. Taylor, and A. Lintern, "Demonstration of a High-Field Short-Period Superconducting Helical Undulator Suitable for Future TeV-Scale Linear Collider Positron Sources," Phys. Rev. Lett. **107**, 1–5 (2011).
[86] D. Abbott *et al.* (PEPPo Collaboration), "Production of highly polarized positrons using polarized electrons at mev energies," Phys. Rev. Lett. **116**, 214801 (2016).
[87] B. King and S. Tang, "Nonlinear compton scattering of polarized photons in plane-wave backgrounds," Phys. Rev. A **102**, 022809 (2020).
[88] S. Tang, B. King, and H. Hu, "Highly polarised gamma photons from electron-laser collisions," Phys. Lett. B **809** (2020).
[89] Yan-Fei Li, Rashid Shaisultanov, Yue-Yue Chen, Feng Wan, Karen Z. Hatsagortsyan, Christoph H. Keitel, and Jian-Xing Li, "Polarized ultrashort brilliant multi-gev γ rays via single-shot laser-electron interaction," Phys. Rev. Lett. **124**, 014801 (2020).
[90] X. Artru, R. Chehab, M. Chevallier, V.M. Strakhovenko, A. Variola, and A. Vivoli, "Polarized and unpolarized positron sources for electron-positron colliders," Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 3868 – 3875 (2008).
[91] Wim Leemans and Eric Esarey, "Laser-driven plasma-wave electron accelerators," Phys. Today **62**, 44–49 (2009).
[92] J. Luo, M. Chen, W. Y. Wu, S. M. Weng, Z. M. Sheng, C. B. Schroeder, D. A. Jaroszynski, E. Esarey, W. P. Leemans, W. B. Mori, and J. Zhang, "Multistage coupling of laser-wakefield accelerators with curved plasma channels," Phys. Rev. Lett. **120**, 154801 (2018).
[93] B. Ananthanarayan and Saurabh D. Rindani, "Cp violation at a linear collider with transverse polarization," Phys. Rev. D **70**, 036005 (2004).