Center-edge asymmetry at e^+e^- linear collider

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Abstract

We study the possibility of uniquely identifying the effects of graviton exchange from other new physics in high energy e^+e^- annihilation into fermion-pairs using the center-edge asymmetry $A_{\rm CE}$.

1 Introduction

There is substantial belief that new physics (NP) beyond the Standart Model (SM) will manifest itself at future proton–proton and electron–positron high energy colliders such as the LHC and the Linear Collider (LC) either directly, as in the case of new particle production, e.g., Z', SUSY or Kaluza-Klein resonances, or inderectly through deviations of observables from the predictions of the SM. The current experimental limits on the new, heavy particles are so high, of the order of several (or tens of) TeV, that one cannot expect them to be directly produced at the energies foreseen for these machines. In this situation, the new interactions can manifest themselves only by indirect, virtual, effects represented by deviations of the measured observables from the SM numerical predictions. The problem, then, is to identify from the data analysis the possible new interactions, because different NP scenarios can in principle cause similar measurable deviations, and for this purpose suitable observables must be defined.

At "low" energies (compared to the above-mentioned large mass scales) the physical effects of the new interactions are conveniently accounted for, in reactions involving the familiar quarks and leptons, by effective *contact-interaction* (CI) Lagrangians that provide the expansion of the relevant transition amplitudes to leading order in the small ratio $\sqrt{s}/\Lambda$ ($\sqrt{s}$ being the c.m. energy).

Familiar classes of contact interactions are represented by composite models of quarks and leptons; exchanges of very heavy Z' with a few TeV mass and of scalar and vector heavy leptoquarks; in the SUSY context, R-parity breaking interactions mediated by sneutrino exchange; bi-lepton boson exchanges; anomalous gauge boson couplings (AGC); virtual Kaluza–Klein (KK) graviton exchange in the context of gravity propagating in large extra dimensions, exchange of gauge boson KK towers or string excitations, *etc.* Of course, this list is not exhaustive, because other kinds of *contact interactions* may well exist.

We briefly discuss the deviations induced by *contact interactions* in the electron–positron annihilation into fermion pairs at the planned Linear Collider energies. In particular, we propose a simple observable that can be used to unambiguously identify graviton KK tower exchange effects in the data, relying on its spin-two character and by "filtering" out contributions of other NP interactions [1].

If deviations from the SM predictions were effectively measured, the identification of the NP source could be attempted by Monte Carlo best fits of the observed effects, and this would apply also to graviton exchange. Alternatively, moments of the differential cross section folded with Legendre polynomial weights appear to be a promising technique to pin down NP effects in the case of electron–positron reactions induced at the SM level by s-channel exchanges [2]. Here, we shall consider a suitably defined combination of integrated cross sections, the so-called "center–edge" asymmetry $A_{\rm CE}$, that allows to disentangle the graviton exchange in a very simple, and efficient, way.

2 Center–edge asymmetry

We consider the process (with $f \neq e, t$)

$$e^+ + e^- \to f + \bar{f}, \tag{1}$$

and, neglecting all fermion masses with respect to $\sqrt{s}$, we can write the differential angular distribution for unpolarized e^+e^- beams in terms of s-channel γ and Z exchanges plus any *contact-interaction* terms in the following form:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \frac{3}{8}\left(1+z^2\right)\sigma + z\,\sigma_{\rm FB} \tag{2}$$

Here, $z \equiv \cos\theta$, with θ the angle between the incoming electron and the outgoing fermion in the c.m. frame, the total cross section, σ, and absolute forward-backward asymmetry, $\sigma_{\rm FB}$, can be written as

$$\sigma = \int_{-1}^{1} \frac{{\rm d}\sigma}{{\rm d}z}{\rm d}z = \frac{1}{4}\left(\sigma_{\rm LL} + \sigma_{\rm LR} + \sigma_{\rm RR} + \sigma_{\rm RL}\right), \tag{3}$$

and

$$\begin{aligned} \sigma_{\rm FB} &\equiv \sigma_{\rm F} - \sigma_{\rm B} = \left(\int_0^1 - \int_{-1}^0\right)\frac{{\rm d}\sigma}{{\rm d}z}{\rm d}z \\ &= \frac{3}{16}\left(\sigma_{\rm LL} - \sigma_{\rm LR} + \sigma_{\rm RR} - \sigma_{\rm RL}\right), \end{aligned} \tag{4}$$

In Eqs. (3) and (4):

$$\sigma_{\alpha\beta} = \sigma_{\rm pt}|\mathcal{M}_{\alpha\beta}|^2, \tag{5}$$

where $\sigma_{\rm pt} \equiv \sigma(e^+e^- \to \gamma^* \to l^+l^-) = 4\pi\alpha^2_{\rm e.m.}/3s$ (for quark-antiquark production a color factor $N_C \simeq 3(1+\alpha_s/\pi)$ would be needed). The helicity amplitudes $\mathcal{M}_{\alpha\beta}$ can be written as

$$\mathcal{M}_{\alpha\beta} = Q_e Q_f + g^e_\alpha\, g^f_\beta\, \chi_Z + \Delta_{\alpha\beta}, \tag{6}$$

where: $\chi_Z = s/(s - M^2_Z + iM_Z\Gamma_Z)$ is the Z propagator; $g^f_{\rm L} = (I^f_{3L} - Q_f s^2_W)/s_W c_W$ and $g^f_{\rm R} = -Q_f s^2_W/s_W c_W$ are the SM left- and right-handed fermion couplings of the Z with $s^2_W = 1 - c^2_W \equiv \sin^2\theta_W$; $Q_e = Q_f = -1$ are the fermion electric charges. The $\Delta_{\alpha\beta}$ functions represent the contact interaction contributions coming from TeV-scale physics.

The structure of the differential cross section (2)–(6) is particularly interesting in that it is equally valid for a wide variety of New Physics (NP) models listed in Table 1. Note that only graviton exchange induces a modified angular dependence to the differential cross section via its z-dependence of $\Delta_{\alpha\beta}$.

We define the generalized center–edge asymmetry $A_{\rm CE}$ as:

$$A_{\rm CE} = \frac{\sigma_{\rm CE}}{\sigma}, \tag{7}$$

in terms of the difference between the central and edge parts of the cross section $(0 < z^* < 1)$

$$\sigma_{\rm CE} = \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right]\frac{{\rm d}\sigma}{{\rm d}z}\,{\rm d}z, \tag{8}$$

Table 1: Parametrization of the $\Delta_{\alpha\beta}$ functions in different models ($\alpha, \beta =$ L, R).

Model	$\Delta_{\alpha\beta}$
composite fermions	$\pm\dfrac{s}{\alpha_{\text{e.m.}}}\dfrac{1}{\Lambda^2_{\alpha\beta}}$
extra gauge boson Z'	$g'^{e}_{\alpha}\, g'^{f}_{\beta}\, \chi_{Z'}$
ADD model	$\Delta_{\text{LL}} = \Delta_{\text{RR}} = f_G\,(1-2\,z)$, $\Delta_{\text{LR}} = \Delta_{\text{RL}} = -f_G\,(1+2\,z)$

and the total cross section (3).

In Table 1 $\Lambda_{\alpha\beta}$ are compositeness scales; $\chi_{Z'}$ is the Z' propagator defined according to χ_Z; $f_G = \lambda\, s^2/(4\pi\alpha_{\text{e.m.}} M_H^4)$ parametrizes the strength associated with massive graviton exchange with M_H the cut-off scale in the KK graviton tower sum. Note that, compared with, e.g., the composite fermion case, the KK graviton effect is suppressed by the (larger) power $(\sqrt{s}/M_H)^4$, so that a lower reach on M_H can be expected in comparison to the constraints obtainable, at the same c.m. energy, on Λ's.

First, let us consider graviton exchange effects. For definiteness we consider the ADD model. From Eqs. (2)–(8) and Table 1 one can derive the asymmetry A_{CE} for the process (1) including graviton tower exchange:

$$A_{\text{CE}} = \frac{\sigma^{\text{SM}}_{\text{CE}} + \sigma^{\text{INT}}_{\text{CE}} + \sigma^{\text{NP}}_{\text{CE}}}{\sigma^{\text{SM}} + \sigma^{\text{INT}} + \sigma^{\text{NP}}}, \tag{9}$$

where "SM", "INT" and "NP" refer to "Standard Model", "Interference" and (pure) "New Physics" contributions. Explicitly, we have

$$\begin{aligned}
\sigma^{\text{SM}}_{\text{CE}} &= N_C\,\frac{\pi\alpha^2_{\text{e.m.}}}{2s}\,\frac{1}{4}\left[(\mathcal{M}^{\text{SM}}_{\text{LL}})^2 + (\mathcal{M}^{\text{SM}}_{\text{RR}})^2 + (\mathcal{M}^{\text{SM}}_{\text{LR}})^2 + (\mathcal{M}^{\text{SM}}_{\text{RL}})^2\right] \\
&\quad \tfrac{4}{3}\,\left[z^*(z^{*2}+3)-2\right], \\
\sigma^{\text{INT}}_{\text{CE}} &= N_C\,\frac{\pi\alpha^2_{\text{e.m.}}}{2s}\,2\,f_G\,\frac{1}{4}\left[\mathcal{M}^{\text{SM}}_{\text{LL}} + \mathcal{M}^{\text{SM}}_{\text{RR}} - \mathcal{M}^{\text{SM}}_{\text{LR}} - \mathcal{M}^{\text{SM}}_{\text{RL}}\right]\,4z^*(1-z^{*2}), \\
\sigma^{\text{NP}}_{\text{CE}} &= N_C\,\frac{\pi\alpha^2_{\text{e.m.}}}{2s}\,f_G^2\,\frac{4}{5}\left[4z^{*5} + 5z^*(1-z^{*2}) - 2\right],
\end{aligned} \tag{10}$$

with

$$\sigma^{\rm SM} = N_C\,\frac{\pi\alpha^2_{\rm e.m.}}{2s}\,\frac{1}{4}\left[(\mathcal{M}^{\rm SM}_{\rm LL})^2+(\mathcal{M}^{\rm SM}_{\rm RR})^2+(\mathcal{M}^{\rm SM}_{\rm LR})^2+(\mathcal{M}^{\rm SM}_{\rm RL})^2\right]\frac{8}{3},$$
$$\sigma^{\rm INT} = 0, \qquad \sigma^{\rm NP}=N_C\,\frac{\pi\alpha^2_{\rm e.m.}}{2s}\,f_G^2\,\frac{8}{5}. \tag{11}$$

Note that, at $z^*=0$ and 1, $\sigma_{\rm CE}=\mp\sigma$, respectively.

In the case of the SM the center–edge asymmetry $A^{\rm SM}_{\rm CE}$ can be obtained from Eqs. (9)–(11) taking $f_G=0$:

$$A^{\rm SM}_{\rm CE}=\frac{\sigma^{\rm SM}_{\rm CE}}{\sigma^{\rm SM}}=\frac{1}{2}\,z^*\,(z^{*2}+3)-1. \tag{12}$$

It is interesting to note that in Eq. (12) the helicity amplitudes in the numerator and denominator cancel and only a ratio of kinematical factors remains in the limit of neglecting external fermion masses. In addition, $A^{\rm SM}_{\rm CE}$ is independent of energy and of the flavour of the final-state fermions. It contains *only* the kinematical variable z^*. Fig. 1 shows $A^{\rm SM}_{\rm CE}$ as a function of z^*. From Eq. (12) one can determine the value of z^* where $A^{\rm SM}_{\rm CE}$ vanishes,

$$z^*_0=(\sqrt{2}+1)^{1/3}-(\sqrt{2}-1)^{1/3}=0.596, \tag{13}$$

corresponding to $\theta=53.4°$ (see the solid curve in Fig. 1).

Graviton exchange in the ADD model affects A_{CE} inducing a deviation from the SM prediction:

$$\Delta A_{\rm CE}=A_{\rm CE}-A^{\rm SM}_{\rm CE}. \tag{14}$$

For $(s/M_H^2)^2\ll 1$, it will be $\sigma^{\rm INT}_{\rm CE}$ which will produce the largest deviation from the expectations of the SM, since this term is of order $(\sqrt{s}/M_H)^4$, whereas the pure NP contribution proportional to f_G^2 in Eqs. (10) and (11) is of the much higher order $(\sqrt{s}/M_H)^8$.

To illustrate the effect of graviton exchange on the center–edge asymmetry, we show in Fig. 2 the z^*-distributions of the deviation $\Delta A_{\rm CE}$, taking as examples the values of M_H indicated in the caption. The deviation $\Delta A_{\rm CE}$ is compared to the expected statistical uncertainties, $\delta A_{\rm CE}$, represented by the vertical bars and given by

$$\delta A_{\rm CE}=\sqrt{\frac{1-(A^{\rm SM}_{\rm CE})^2}{\epsilon_f\,\mathcal{L}_{\rm int}\,\sigma^{\rm SM}}}. \tag{15}$$

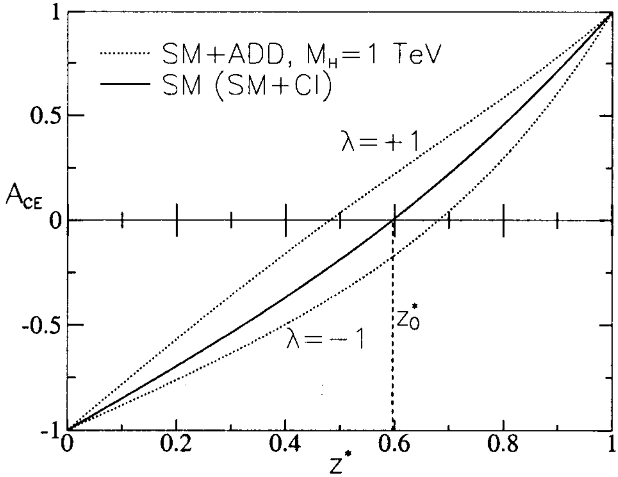

Figure 1: Tree-diagram result for A_{CE} for the process $e^+e^- \to l^+l^-$ ($l = \mu, \tau$) as a function of z^* in the SM and in the ADD model with $M_H = 1$ TeV and $\lambda = \pm 1$.

Here, $\mathcal{L}_{\rm int}$ is the integrated luminosity, and ϵ_f the efficiency for reconstruction of $f\bar{f}$ pairs. We will assume that the efficiencies of identifying the final state fermions are rather high: 100% for $l = \mu$, τ, 80% for $f = b$, and 60% for $f = c$. Fig. 2 qualitatively indicates that, for the chosen values of the c.m. energy $\sqrt{s}$ and $\mathcal{L}_{\rm int}$, the reach on M_H will be of the order of 2.5 TeV.

Now, let us consider the conventional *contact-interaction*-like effects parametrized by z-independent $\Delta_{\alpha\beta}$ summarized in Table 1. Application of Eq. (7) to composite-like contact interactions is straightforward, the result can be written as:

$$A_{\rm CE}^{\rm SM+CI} = \frac{\sigma_{\rm CE}^{\rm SM+CI}}{\sigma^{\rm SM+CI}} = \frac{1}{2}\, z^* \left(z^{*2} + 3\right) - 1., \qquad (16)$$

This result is *identical* to $A_{\rm CE}^{\rm SM}$ defined by Eq. (12). In other words, $A_{\rm CE}$ has the form (16) in the SM and will remain so even if *contact-interaction*-like effects are present. Thus, conventional contact-interaction effects, being described by current–current interactions, yield *the same* center–edge asymmetry as the Standard Model. The reason is simply that both these interactions are described by vector currents, as opposed to the tensor couplings of gravity. The deviation of $A_{\rm CE}$ from the SM (and SM+CI) prediction is clearly a signal of the spin-2 particle exchange. Thus,

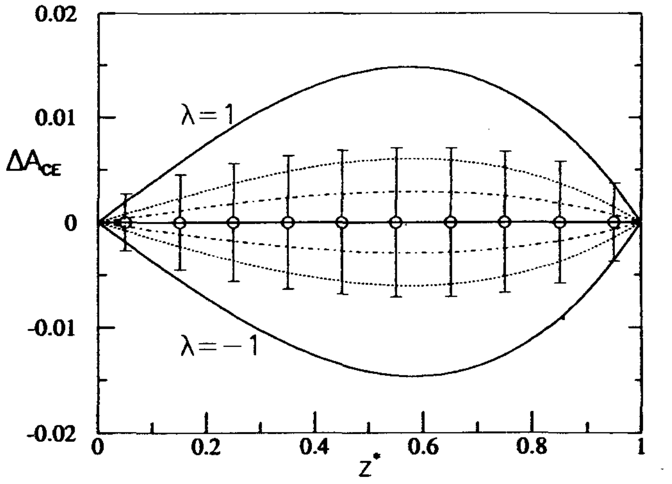

Figure 2: The deviation of $A_{\rm CE}$ [cf. Eq. (14)] from the SM (or SM+CI) expectations (at tree level) as a function of z^* for the process $e^+e^- \to l^+l^-$ for $M_H = 2$ (solid), 2.5 (dotted), and 3 TeV (dash-dotted), $\lambda = \pm 1$ and $\sqrt{s} = 0.5$ TeV. The expected statistical uncertainties at $\mathcal{L}_{\rm int} = 50$ fb^{-1} are shown as error bars.

it is clear that a non-zero value of $\Delta A_{\rm CE}$ can provide a clean signature for graviton, or more generally, spin-2 exchange in the process $e^+e^- \to \bar{f}f$.

In case of longitudinally polarized beams, with P and $\bar{P}$ the degrees of polarization of the electron and positron beams, respectively, the polarized differential cross section can then be written as

$$\frac{{\rm d}\sigma}{{\rm d}z} = \frac{D}{4}\left[(1-P_{\rm eff})\left(\frac{{\rm d}\sigma_{\rm LL}}{{\rm d}z}+\frac{{\rm d}\sigma_{\rm LR}}{{\rm d}z}\right)+(1+P_{\rm eff})\left(\frac{{\rm d}\sigma_{\rm RR}}{{\rm d}z}+\frac{{\rm d}\sigma_{\rm RL}}{{\rm d}z}\right)\right], \tag{17}$$

where $D = 1-P\bar{P}$ and $P_{\rm eff} = (P-\bar{P})/(1-P\bar{P})$ is the effective polarization. For example, $P_{\rm eff} = \pm 0.95$ and $D \approx 1.5$ for $P = \pm 0.8$ and $\bar{P} = \mp 0.6$.

3 Identification reach

To assess a realistic reach on the mass scale M_H we can consider a χ^2-function made of the deviation of the asymmetry $A_{\rm CE}$ from its SM value. For a fixed integrated luminosity this can be done using the statistical errors as well as the systematic errors. We find that, to a very large extent, the systematic errors associated with the uncertainties expected on the luminosity measurements cancel out, and the same is true for the systematic errors induced by the uncertainty on beam polarizations. Accordingly, the errors on $A_{\rm CE}$ are largely dominated by statistics. In this estimation we assume the values $\delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int} = \delta P/P = \delta\bar{P}/\bar{P} = 0.5\%$. We take the beam polarization to be 80% and 60% for electrons and positrons, respectively, and employ a 10° angular cut around the beam pipe, i.e., $z_{\rm cut} = 0.98$. Since most of the error is statistical in origin, we expect the bound on M_H to scale as $\sim (\mathcal{L}_{\rm int} s^3)^{1/8}$. We also take into account the radiative corrections using the existing codes, e.g., ZFITTER, adapted for present analysis.

Summing over $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$ and $c\bar{c}$ final states (the top-quark is excluded as its mass effects would alter the angular distribution one can perform a conventional χ^2 analysis:

$$\chi^2 = \sum_{f=\mu,\tau,c,b} \frac{(\Delta A^f_{\rm CE})^2}{(\delta A^f_{\rm CE})^2}, \tag{18}$$

keeping $z^* = z^*_0$ fixed. This leads to the 5σ identification reach as a function of integrated luminosity with energy $\sqrt{s} = 0.5$ and 1 TeV shown in Fig. 3. Specifically, for $\sqrt{s} = 0.5 - 1$ TeV machines with integrated luminosity 1 ab^{-1} the identification reach with double beam polarization is found to be $(7-6) \times \sqrt{s}$.

4 Summary

We conclude with a summary of the main points and some observations. We have developed a specific approach based on an integrated observable, the center-edge asymmetry $A_{\rm CE}$, to search for and identify spin-2 graviton exchange with uniquely distinct signature. Indeed, the spin-2 graviton KK exchanges contribute to the asymmetry $A_{\rm CE}$, whereas no deviations from the SM are induced by other kinds of new physics such as the composite-like contact interactions, a heavy vector boson Z' listed in Table 1. Both in the SM and in any new physics scenario described by effective current–current interactions, the asymmetry $A_{\rm CE}$ is identical for any value of the parameter z^*.

Initial electron and positron beam polarization appears to increase the sensitivity to graviton exchange, but their impact on the mass scale parameter $M_{\rm H}$ is not dramatic due to the large power $(\sqrt{s}/M_{\rm H})^4$ that

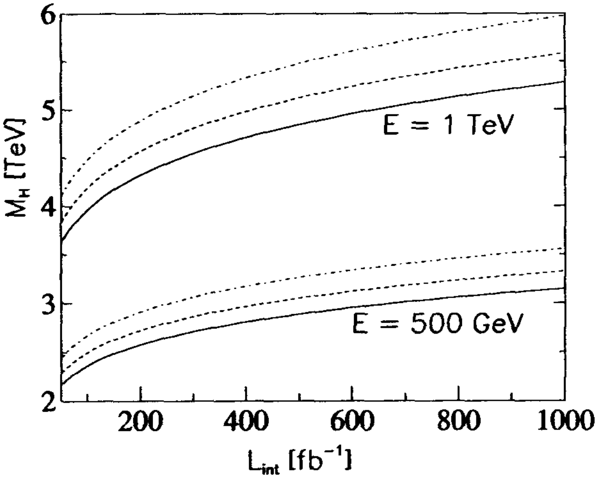

Figure 3: 5σ reach on the mass scale M_H *vs.* integrated luminosity from the process $e^+e^- \to f\bar{f}$, with f summed over μ, τ, b, c, and at energies 0.5 and 1 TeV. Solid: unpolarized; dashed: electrons polarized, $P = 0.8$; dash-dotted: both beams polarized, $P = 0.8$, $\bar{P} = -0.6$.

parametrizes the graviton coupling. In particular, for an e^+e^- linear collider with energy $\sqrt{s} = 0.5$ and 1 TeV, with integrated luminosity 1 ab^{-1}, double beam polarization and a 10° angular cut, the 5σ identification reach is found to be $M_H \leq 3.5$, 6 TeV, respectively.

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References

[1] For details of the analysis and original references, see P. Osland, A. A. Pankov and N. Paver, Phys. Rev. D **68**, 015007 (2003).

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