Publication of A_{LR} Predictions for Bhabha Scattering

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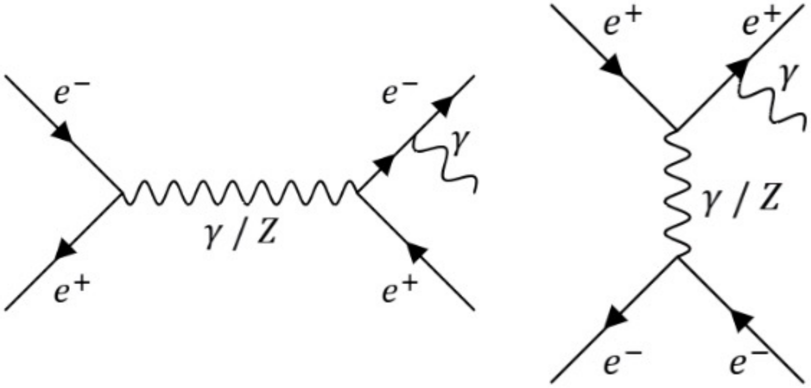

University of Victoria

Comparing Two NLO Theory Calculations of A_{LR}

We compare calculations of an NLO calculation
[A. G. Aleksejevs, S. G. Barkanova, Y. M. Bystritskiy, and V. A. Zykunov, *“Electroweak Corrections with Allowance for Hard Bremsstrahlung in Polarized Bhabha Scattering”,* Physics of Atomic Nuclei 83, 463 (2020)]

with those of an independent NLO calculation using the ReneSANCe Monte Carlo generator
[R. Sadykov and V. Yermolchyk, *“Polarized NLO EW cross section calculations with ReneSANCe”,* Computer Physics Communications 256, 107445 (2020)]
(See Additional Material for parameter settings used to match calculations of Aleksejevs *et al*)

and:

- Determine the level of agreement between them;
- Project the sensitivity of the Chiral Belle A_{LR} measurement; and
- Estimate the scale of the NNLO correction

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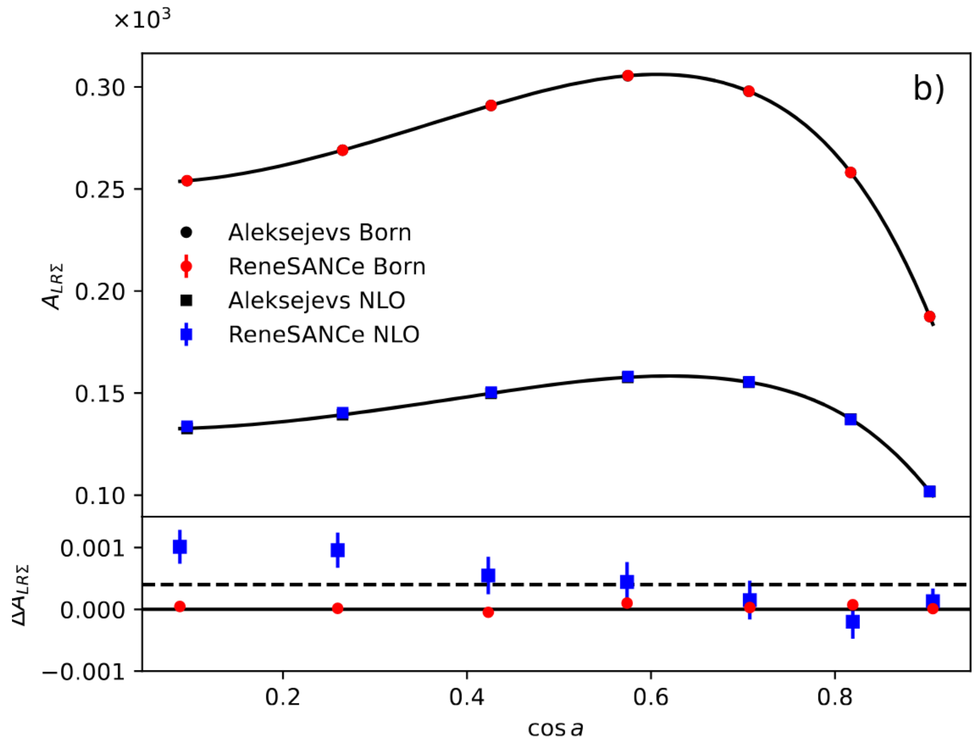


- Comparison of calculations of integrated A_{LR} in Bhabhas from Aleksejevs *et al* and ReneSANCe for an angular acceptance of final-state electron angle "a" integrated between a and 180°-a. Line is a cubic spline.
- **The average absolute difference between the calculations is 4.4×10^{-7} equivalent to a relative difference of 0.3%**

Sensitivity to A_{LR} : Statistics

Use the published Belle II efficiency for selecting Bhabha events from our luminosity paper: *"Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment", Chinese Physics C 44, 021001 (2020)*:
for $|\cos\theta| < 0.819$ the efficiency = 0.3593 and the Bhabha cross-section is 17.4nb.

Assuming Chiral Belle achieves it's goal of a 70% polarization, and taking A_{LR} = 0.00012 from ReneSANCe for the angular acceptance of $|\cos\theta| < 0.819$, a measured $A_{LR}\langle Pe\rangle$= 0.000098 is predicted, with a **statistical uncertainty of 2.3% for 40 ab^{-1} of data**

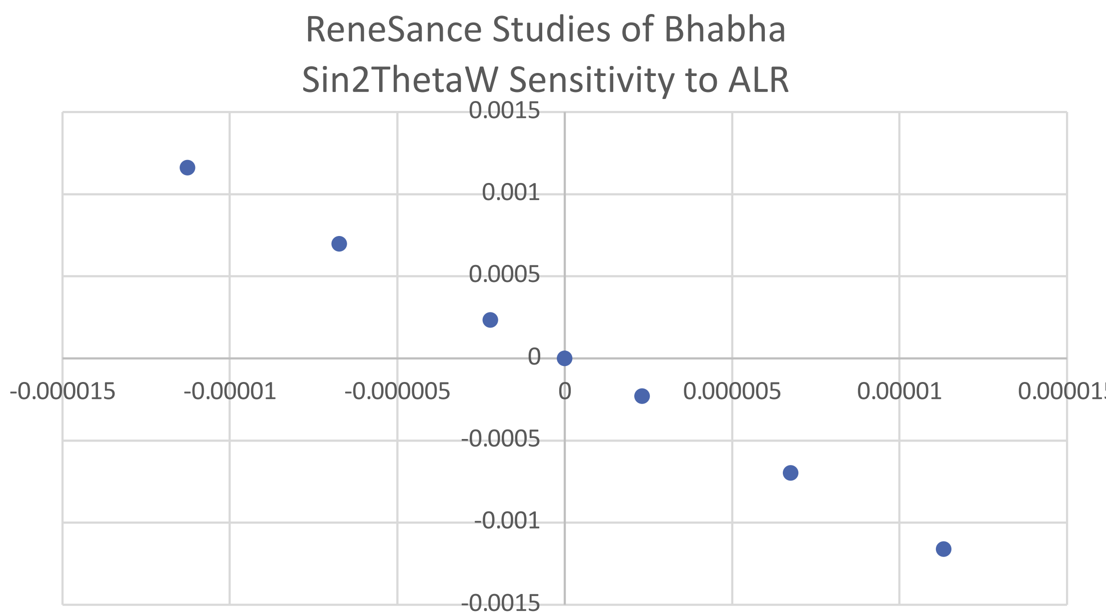
Sensitivity to A_{LR}: Systematics

Dominant systematic uncertainties expected to arise from:

- Background modelling: Belle II lumi paper (*Chinese Physics C 44, 021001 (2020)*) quotes a total background level of 0.07% from $u\bar{u}$, $d\bar{d}$, $\tau^+\tau^-$
  $d\bar{d}$ contributes the largest effect as $A_{LR}^{d\bar{d}} \sim$ -0.020 is the largest. Conservatively assume the entire background is $d\bar{d}$ and it is controlled to 10%, projects a 1% relative uncertainty on A_{LR}^{ee}
- Knowledge of the beam polarization: from tau polarimetry and (independently) from Compton polarimetry yields a relative uncertainty of 0.4% for 70% polarization
- Polar angle acceptance uncertainty: ECL location is known to within 0.11 mm along beam axis [*Belle II, Chinese Physics C 49, 013001 (2025)*] corresponding to acceptance uncertainty of 36 micro-radians. Propagating this uncertainty through ReneSANCe gives a 0.06% uncertainty on A_{LR}^{ee}
- Knowledge of the center-of-mass energy of the collisions: assuming it is known to ~5 MeV and propagating this uncertainty through ReneSANCe gives a 0.07% on A_{LR}^{ee}

Total relative systematic uncertainty on A_{LR}^{ee} estimated to 1%, dominated by background modelling

$\sin^2\theta_W$ Sensitivity to A_{LR}



As suggested by authors of ReneSANCE, we shift values of M_w in ReneSANCE generator to determine $\sin^2\theta_W$ sensitivity to A_{LR}

For 40 ab^{-1}, a 70% polarization, and detector acceptance of **$|\cos\theta| < 0.90$**, the projected precision from the Bhabha A_{LR} measurement is **$\sigma(\sin^2\theta_W) = \pm 0.00028$**

For 40 ab^{-1}, a 70% polarization, and detector acceptance of **$|\cos\theta| < 0.819$**, the projected precision from the Bhabha A_{LR} measurement is **$\sigma(\sin^2\theta_W) = \pm 0.00032$**

$\sin^2\theta_W$ Sensitivity

Chiral Belle uncertainty is comparable to combined SLD-LEP uncertainty of ±0.00024 on $\sin^2\theta_W$ at the Z^0 pole involving only the Z^0-electron couplings - but at 10GeV
(Note: recent CMS result for $\sin^2\theta_W$ from Z^0-> e+e- is ±0.00041)

Also comparable to the MOLLER experiment's projected uncertainty of (±0.00028) at the lower 100 MeV energy scale

Chiral Belle including tau and muons – assuming lepton universality gives an uncertainty of ±0.00019 - would be single most precise measurement of $\sin^2\theta_W$ (NB: ±0.00016(LEP + SLC))
Only precise measurement at 10GeV

Scale of NNLO Contributions

Scale of the NNLO contributions is conventionally estimated as α×NLO contribution, i.e. on the order of 1% of the NLO contributions, which translates into an uncertainty on the asymmetry of $\delta A_{LR}^{NNLO} \sim 1.5 \times 10^{-6}$

NNLO contributions to $e^+e^- \to \tau^+\tau^-$ cross-section calculated and reported in Kollastzsch *et al, SciPost Phys. 15, 104 (2023).*
show NLO effects act as ~18% correction to Born level cross-section, while NNLO effects contribute a ~0.5% correction to Born level (~3% correction to NLO values).
But this process has no t-channel – as the Bhabha scattering does

NNLO carried out for the MOLLER experiment for polarized e^-e^- scattering (t and u-channel processes but no s-channel) and the NNLO quadratic and reducible contributions were found to contribute a ~5% correction to the asymmetry (~12% correction to the NLO contribution)

Scale of NNLO Contributions

Based on these considerations, the scale of the NNLO effects on the Bhabha scattering A_{LR}^{ee} are expected to be significant compared to the projected experimental uncertainties from Chiral Belle of ~2.5% (stat+sys) with 70% polarization and integrated lumi of 40 ab^{-1}

⇒ a dedicated NNLO calculation of this process is required

Plans being made for a new postdoc (Mahumm Ghaffar) at Memorial University of Newfoundland to start working on these NNLO calculations later this summer

Paper has been accepted for publication in PRD

Physical Review D

ACCEPTED PAPER

Left-right asymmetry calculation comparisons and projected sensitivity to the weak mixing angle in polarized Bhabha scattering at 10.58 GeV

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Abstract

Consideration is being given to upgrading the SuperKEKB electron-positron collider with the introduction of electron-beam polarization. This would enable a unique precision electroweak physics program that opens new ways to search for physics beyond the Standard Model. The upgrade would enable Belle II to make a number of high precision measurements, one of which is the left-right cross-section asymmetry in the \epem → \epem Bhabha scattering process. The expected level of precision in such a measurement will require the theoretical values of the asymmetry to be calculated at least to the next-to-leading order (NLO) level, and the implementation of simulation event generators with a similar level of precision. In this study, we compare the calculations of the ReneSANCe Monte Carlo generator with those of an independent NLO calculation to determine the level of agreement in this process. An average difference of 0.3% between the calculations is found. Using the published Belle II efficiency for selecting Bhabha events and assuming a 40 ab^{-1} dataset having 70% polarization, the projected uncertainty on the weak mixing angle, , is calculated using ReneSANCe to be ± 0.00032 or better. Combining this with left-right asymmetry measurements from muons and taus under the assumption of lepton universality yields a projected overall uncertainty of ± 0.00019 on with SuperKEKB upgraded to have polarized electron beams.

Additional Material

Comparing Two NLO Theory Calculations of A_{LR}

To compare ReneSANCe calculations to those of Aleksejevs *et al* the following ReneSANCe default SM parameters were changed to correspond to those in Aleksejevs *et al:*

widths of the W boson and the top quark are set to 0,
M_{Higgs}=125GeV, M_Z =91.1876, M_W=80.4628GeV,
M_u=69.83MeV, M_d=69.84MeV, M_S=0.15GeV, M_c=1.2GeV,
M_b=4.6GeV, M_t=174GeV
CM energy = 10.577 GeV
soft photon cutoff, *ome,* set to 0.002
(Note that earlier comparisons had different *ome* following advice of A. Aleksejevs, likely a misunderstanding.)