Precision Electroweak Physics at Belle II with a Polarized Electron Beam SuperKEKB Upgrade

J. Michael Roney
University of Victoria
20 July 2022

On behalf of the Belle II & SuperKEKB e- Polarization Upgrade Working Group
2022/07/20

Precision EW Physics at Belle II with a Polarized Electron Beam SuperKEKB Upgrade

April 13, 2022

Contents

1 Introduction 1

2 Precision Electroweak Program
   2.1 Muon Pair $A_{LR}$ 2
   2.2 Tau Pair $A_{LR}$ 6
   2.3 Charm and Beauty $A_{LR}$ 7
      2.3.1 Introduction 7
      2.3.2 Training and evaluation of the model 7
      2.3.3 Evaluation 7
      2.3.4 Classification of $q^2$ 9
      2.3.5 Classification of $b$ 9
   2.3.6 Lepton requirement study 9
   2.3.7 Beauty $A_{T}$ 10
   2.3.8 Charm $A_{T}$ 12
   2.4 Bhabha $A_{LL}$ 13

3 Tau $g - 2$ 14

4 Tau EDM 17

5 Tau LFV 18

6 QCD: Dynamical mass generation studies with polarized beams 19

7 Polarized Source
   7.1 Beam Generation 21
      7.1.1 Cathode Production and Testing 22
   7.2 Linac Transport 22

8 Beam-Beam Effects on Polarization 23
Upgrading SuperKEKB with polarized electrons

Opens New Windows for Discovery with Belle II

• Extremely rich and unique high precision electroweak program
• Probe of Dark Sector
• $\tau$ Magnetic Form factor $F_2(10\text{GeV}) \rightarrow g-2 \ @ \ 10^{-5}$
• Polarized Beam also provides:
  • Improved precision measurements of $\tau$ Michel Parameters, $\tau$ electric dipole moment (EDM) and reduces backgrounds in $\tau\rightarrow\mu\gamma$ and $\tau\rightarrow e\gamma$ precision leading to significantly improved sensitivities
• hadronic studies
Replace short dipoles with longer ones (LER)

Redesign the lattices of HIGH ENERGY RING (HER) & LOW ENERGY RING (LER) to squeeze the emittance

TiN-coated beam pipe with antechambers

To obtain x40 higher luminosity
Polarization in SuperKEKB

• Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment)

• Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)

• **Inject vertically polarized electrons** into the High Energy Ring (HER) - needs low enough emittance source to be able to inject.

• **Rotate spin to longitudinal before IP**, and then back to vertical after IP using solenoidal and dipole fields

• Use Compton polarimeter to monitor longitudinal polarization with <1% absolute precision, higher for relative measurements (arXiv:1009.6178) - needed for real time polarimetry

• Use tau decays to get absolute average polarization at IP
A New Path for Discovery in a Precision Neutral Current Electroweak Program

- **Left-Right Asymmetries** ($A_{LR}$) yield high precision measurements of the neutral current vector couplings ($g_V$) to each of five fermion flavours, $f$:
  - beauty (D-type)
  - charm (U-type)
  - tau
  - muon
  - electron

Recall: $g_V^f$ gives $\theta_W$ in SM

\[
\begin{align*}
g_A^f &= T_3^f \\
g_V^f &= T_3^f - 2Q_f \sin^2 \theta_W
\end{align*}
\]

as well as light quarks

$T_3 = -0.5$ for charged leptons and D-type quarks
+0.5 for neutrinos and U-type quarks
The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception

-2.5 \sigma discrepancy in forward-backward asymmetry of the b quark

Requires modifications of (right-handed) Zb couplings

\[ g_{L,R}^b = g_{L,R}^{b\text{SM}} + \delta g_{L,R}^b \]
Existing tension in data on the Z-Pole:

3.2σ comparing only $A_{LR}$ (SLC) and $A_{0,b}^0$ (LEP)
‘Chiral Belle’ -> Left-Right Asymmetries

• Measure difference between cross-sections with left-handed beam electrons and right-handed beam electrons normalized by their sum

• Same technique as SLD $A_{LR}$ measurement at the Z-pole giving single most precise measurement of:

$$\sin^2 \theta_{\text{eff}}^{\text{lepton}} = 0.23098 \pm 0.00026$$

• At 10.58 GeV, polarized $e^-$ beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via $Z-\gamma$ interference:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}} \left( \frac{G_F s}{4\pi \alpha Q_f} \right) g_A^e g_V^f \langle Pol \rangle$$

$$\propto T_3^f - 2Q_f \sin^2 \theta_W$$
Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

\[ A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}} \left( \frac{G_F s}{4\pi\alpha Q_f} \right) g_A^e g_V^f \langle Pol \rangle \]

\[ \propto T_3^f - 2Q_f \sin^2 \theta_W \]

\[ \langle Pol \rangle = 0.5 \left\{ \frac{N_{e^-}^R - N_{e^-}^L}{N_{e^-}^R + N_{e^-}^L} \right\}_R - \left\{ \frac{N_{e^-}^R - N_{e^-}^L}{N_{e^-}^R + N_{e^-}^L} \right\}_L \]

For \( A_{LR} \) calculation with NLO corrections for mu-pair final state, see: Aleksejevs, Barkanova, Roney, Zykunov “NLO radiative corrections for Forward-Backward and Left-Right Asymmetries at a B Factory”, arXiv:1801.08510
International collaboration of Accelerator and Particle Physicists

➤ Theorists currently working on SM Electroweak calculations:

Aleks Aleksejevs & Svetlana Barkanova, (Memorial U Newfoundland), Vladimir Zykunov & Yu.M.Bystritskiy (DUBNA)

\[ e^+e^- \rightarrow \mu^+\mu^- \]

\[ A_{LR}^{\mu\mu} \text{ vs } \sin^2 \theta_{W}^{\text{eff}} \]

\[ \text{e}^+\text{e}^- \rightarrow \text{e}^+\text{e}^- \]

\[ a=10^\circ \text{ & energy of photons } < 2\text{GeV} \]

New generator: ReneSANCe


New generator with beam polarization capable of producing Bhabhas.

Polarization in each beam and special mode to efficiently calculate $A_{LR}$ without event generation output.

Comparing ReneSANCe with results published in:

Using $M_W$ variations with ReneSANCe, can find $\delta \sin^2 \theta_W / \delta A_{LR}$

$A_{LR}$ as a function of acceptance angle where $z$ is e- direction in centre-of-mass
Using $M_W$ variations with ReneSANCe, can find $\frac{\delta \sin^2 \theta_W}{\delta A_{LR}}$

Belle II has published a luminosity paper with Bhabha acceptance in the central part of the detector:

*F. Abudinén et al, Belle II Collaboration, Chin.Phys.C 44 (2020) 2, 021001*

Reports: Cross-section = 17.4nb, efficiency=36%
With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

<table>
<thead>
<tr>
<th>Final State Fermion</th>
<th>$\sin^2 \Theta_W$ for all LEP+SLD measurements combined $WA = 0.23153 \pm 0.00016$</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-quark</td>
<td>$-0.0200 \pm 0.0001$</td>
</tr>
<tr>
<td>c-quark</td>
<td>$+0.00546 \pm 0.00003$</td>
</tr>
<tr>
<td>tau</td>
<td>$-0.00064 \pm 0.000015$</td>
</tr>
<tr>
<td>muon</td>
<td>$-0.00064 \pm 0.00009$</td>
</tr>
<tr>
<td>Electron (barrel) (17nb, eff. = 0.36)</td>
<td>$+0.00015 \pm 0.00003$</td>
</tr>
</tbody>
</table>

Relative Error

- b-quark (selection eff. = 0.3): 0.5%
- c-quark (eff. = 0.15): 0.5%
- tau (eff. = 0.25): 2.4%
- muon (eff. = 0.5): 1.5%
- Electron (barrel) (17nb, eff. = 0.36): 2.0%
## High Precision Neutral Current Vector Coupling Measurements

<table>
<thead>
<tr>
<th>Fermion</th>
<th>$g_V^f$ (Standard Model)</th>
<th>$g_V^f$ (World Average)</th>
<th>$\sigma(g_V^f)$ (Chiral Belle 40ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-quark</td>
<td>-0.3437 ± 0.0001</td>
<td>-0.3220 ± 0.0077</td>
<td>0.0020 (4 x improvement)</td>
</tr>
<tr>
<td>c-quark</td>
<td>0.1920 ± 0.0002</td>
<td>0.1873 ± 0.0070</td>
<td>0.0010 (7 x improvement)</td>
</tr>
<tr>
<td>Tau</td>
<td>-0.0371 ± 0.0003</td>
<td>-0.0366 ± 0.0010</td>
<td>0.0008</td>
</tr>
<tr>
<td>Muon</td>
<td>-0.0371 ± 0.0003</td>
<td>-0.03667 ± 0.0023</td>
<td>0.0005 (4 x improvement)</td>
</tr>
<tr>
<td>Electron</td>
<td>-0.0371 ± 0.0003</td>
<td>-0.03816 ± 0.00047</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Combined analysis (assuming universality) : $\sigma(g_V^f) = 0.00033_{\text{stat}}^{+0.00018}_{-0.00008}$ [cf. SM error of ±0.0003]

2.8σ tension between SM and WA

2022/07/20
Highest Precision b and c Neutral Current Vector Coupling Measurements

Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

**c-quark:**
Chiral Belle ~7 times more precise

**b-quark:**
Chiral Belle ~4 times more precise

with 20 ab$^{-1}$
b-to-c Neutral Current Vector Coupling Universality Ratio

The ratio \( \frac{A_{LR}^{f_1}}{A_{LR}^{f_2}} \) provides a measurement of \( \frac{g_V^{f_1}}{g_V^{f_2}} \)

\(<P> \) cancels in ratio: uncertainty dominated by statistics
Avoid hadronization uncertainties in determining \( g_V^b \)
that were significant in extraction from \( A_{FB}^b \) at Z-pole

<table>
<thead>
<tr>
<th>g_V^b / g_V^c</th>
<th>SM</th>
<th>World Average^1</th>
<th>Chiral Belle 20 ab(^{-1})</th>
<th>Chiral Belle 50 ab(^{-1})</th>
<th>Chiral Belle 250 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>± .0005</td>
<td>± .082</td>
<td>Improves x 14</td>
<td>Improves x 24</td>
<td>Improves x 50</td>
</tr>
<tr>
<td>Relative error:</td>
<td>0.18%</td>
<td>4.8%</td>
<td>0.32%</td>
<td>0.19%</td>
<td>0.09%</td>
</tr>
</tbody>
</table>

1 - Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD
sin^2 \( \Theta_W \) - all LEP+SLD measurements combined \( WA = 0.23153 \pm 0.00016 \)
sin^2 \( \Theta_W \) - Chiral Belle combined leptons with 40 ab\(^{-1}\) have error \( \sim \) current WA

\( b \)-\( c \) UNIVERSALITY
70% polarized e\(^-\) beam provides a measurement of
The ratio \( \frac{A_{LR}^{f_1}}{A_{LR}^{f_2}} \) cancels in ratio: uncertainty dominated by statistics
Avoid hadronization uncertainties in determining \( g_V^b \)
that were significant in extraction from \( A_{FB}^b \) at Z-pole

1 - Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD
sin^2 \( \Theta_W \) - all LEP+SLD measurements combined \( WA = 0.23153 \pm 0.00016 \)
sin^2 \( \Theta_W \) - Chiral Belle combined leptons with 40 ab\(^{-1}\) have error \( \sim \) current WA

Relative error: 0.18% 4.8% 0.32% 0.19% 0.09%
Chiral Belle probes both high and low energy scales

Chiral Belle: $\sigma < 0.0002$ with 40 ab$^{-1}$
Using only clean leptonic states

- Precision probe of running of the weak mixing angle
- Being away from Z-pole opens NP sensitivities not available at the pole

• Measurements of $\sin^2 \theta_{\text{eff}}^{\text{lepton}}$ of using lepton pairs of comparable precision to that obtained by LEP/SLD, except at 10.58 GeV
  • sensitive to $Z' > \text{TeV}$ scale; can probe purely $Z'$ that only couple to leptons: complementary to direct $Z'$ searches at LHC which couple to both quarks and leptons
Running of $\sin^2\theta_W(Q^2)$: Window on the Dark Sector

- Dark blue band shows $Q^2$-dependent shift in $\sin^2\theta_W$ due to 15 GeV parity-violating dark Z

- Adapted from Fig. 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015.
- Red bars shows expected $\pm1$ sigma uncertainty = 0.0002 with 40 ab$^{-1}$ at Chiral Belle [placed at arbitrary positions].
Chiral Belle probes both high and low energy scales

Global interest in this EW physics:

- LHC experiments
- APV measurements at lower energy scales
- Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{\text{eff}}^{\text{electron}}$ below 100MeV with similar precision (note: Moller is only sensitive to electron couplings.)
- EIC can measure $\sin^2\theta_{\text{eff}}$ in similar kinematic region, but with less precision, and without accessing mu, tau, charm or beauty
- Next generation high energy e+e- colliders: ILC (where polarization is planned) & FCC-ee
Chiral Belle also provides:

• **Improved precision measurements of electric dipole moment (EDM) and information on the Magnetic Form factor $F_2(10\text{GeV})$**
  
  
  
  
  “Towards testing the magnetic moment of the tau at one part per million”

• **τ Michel Parameters**
  
  • Denis Epifanov talk at Tau 2021 the Russian Super Tau-Charm Factory (STCF) which will operate with e- polarized beams

• **Reduces backgrounds in $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow e \gamma$** – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
  
  • See: arXiv:1008.1541v1 [hep-ex]

• **Polarized e+e- annihilation into a polarized $\Lambda$ or a hadron pair experimentally probes dynamical mass generation in QCD**
Electric and Magnetic Moments of the $\tau$ Lepton

\[ \Gamma^\mu = F_1 \left( q^2 \right) \gamma^\mu + F_2 \left( q^2 \right) \frac{1}{2m_{\tau}} i\sigma^{\mu\nu} q^\nu + F_3 \left( q^2 \right) \frac{1}{2m_{\tau}} \sigma^{\mu\nu} q^\nu \gamma_5 \]

- $F_1 \left( q^2 \right)$, $F_2 \left( q^2 \right)$ are called the Dirac and Pauli; $F_1(0) = 1$; $F_2(0) = a_\tau$

- $g = 2 \cdot \left[ F_1 \left( 0 \right) + F_2 \left( 0 \right) \right] = 2 + 2F_2 \left( 0 \right)$

- $d_\gamma^{\tau} = \frac{e}{2m_{\tau}} \cdot F_3 \left( 0 \right)$

- $\frac{\alpha}{2\pi} \approx 0.001 161 4$

Leading ‘Schwinger’ term
Charge asymmetry along spin direction: \( \text{EDM} \neq 0 \Rightarrow \text{CP violation} \)
SM expectation \( \mathcal{O}(10^{-37}) \) e·cm far below experimental sensitivity
New physics in loops can enhance EDM of \( \tau \) lepton \( \sim \mathcal{O}(10^{-19}) \) e·cm


**With 40ab\(^{-1}\) + 70% Polarization: accesses \( \tau \) EDM at the \( 10^{-20} \) e·cm level** (using J. Bernabéu et al, Nucl. Phys. B763:283–292, 2007)

**For the magnetic moment:**

\[
a_\ell = \frac{(g_\ell - 2)}{2}
\]

Large deviation in anomalous magnetic moment of muon:

\[
a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11} [4.2\sigma]
\]

Expectation from Minimal Flavour Violation:

\[
a_\tau^{\text{BSM}} \sim a_\mu^{\text{BSM}} \left( \frac{m_\tau}{m_\mu} \right)^2 \sim 10^{-6}
\]

Current bound in tau \( \sim \mathcal{O}(10^{-2}) \)
Chiral Belle reach \( \sim \mathcal{O}(10^{-5}) \) with 50ab\(^{-1}\)
Magnetic Moment of the $\tau$ Lepton with Polarized Beams

Coordinate system for hadronic tau-pair $e^+e^- \rightarrow \tau^+\tau^- \ ; \tau^+ \rightarrow h^+ \bar{\nu}_\tau$ and $\tau^- \rightarrow h^- \nu_\tau$ events

Using z-axis is aligned $\tau^-$ momentum, $\theta_{\tau^-}$ is production angle of $\tau^-$ with respect to the e-beam direction in CM, and the azimuthal and polar angles of the produced hadrons, $h^\pm$, in $\tau^\pm$ rest frame, are $\phi^*_{\pm}$ and $\theta^*_{\pm}$.

$\tau^-$ pair production plane and $\tau^\pm$ direction of flight are fully reconstructed as described in J. H. Kuhn, Phys. Lett. B 313, 458 (1993)

\[
A_{RL} = \frac{\frac{d^2\sigma_{Re}}{dz^+dz}}{\frac{d^2\sigma_{Le}}{dz^-dz}} - \frac{\frac{d^2\sigma_{Le}}{dz^+dz}}{\frac{d^2\sigma_{Re}}{dz^-dz}}
\]

$A^\pm = \frac{1}{2\sigma} \left[ \int_{-\pi/2}^{\pi/2} \left( \frac{d\sigma_{Re}}{d\phi_\pm} - \frac{d\sigma_{Le}}{d\phi_\pm} \right) d\phi_\pm - \int_{-3\pi/2}^{3\pi/2} \left( \frac{d\sigma_{Re}}{d\phi_\pm} - \frac{d\sigma_{Le}}{d\phi_\pm} \right) d\phi_\pm \right]$

$\sigma^{Re}$: Right Handed beam Xsec

$\sigma^{Le}$: Left Handed beam Xsec

$\sigma_{FB}(\pm) = \sigma_{Pol}^{\pm} - \sigma_{Pol}^{\mp}$

To get an observable sensitive to the relevant signal define the azimuthal transverse asymmetry as

\[ A_T^\pm = \frac{\sigma_R^\pm|_{\text{Pol}} - \sigma_L^\pm|_{\text{Pol}}}{\sigma} \]

\[ = \mp \alpha_{\pm} \frac{3\pi}{8(3 - \beta^2)\gamma} \left[ |F_1|^2 + (2 - \beta^2)\gamma^2 \text{Re} \{F_2\} \right] \]

Then, we define the longitudinal asymmetry as

\[ A_L^\pm = \frac{\sigma_{FB}^\pm(+) - \sigma_{FB}^\pm(-)|_{\text{Pol}}}{\sigma} \]

\[ = \mp \alpha_{\pm} \frac{3}{4(3 - \beta^2)} \left[ |F_1|^2 + 2 \text{Re} \{F_2\} \right] \]

\[ \text{Re}(F_2^{\text{eff}}) = \mp \frac{8(3 - \beta^2)}{3\pi\gamma\beta^2\alpha_{\pm}} \left( A_T^\pm - \frac{\pi}{2\gamma} A_L^\pm \right) \]

\[ \gamma = \frac{E_\tau}{m_\tau} \quad \alpha = \frac{(m_\tau^2 - 2m_h^2)}{(m_\tau^2 + 2m_h^2)} \]

\[ |F_1|^2 \text{ cancels in the difference} \]
Magnetic Moment of the $\tau$ Lepton


Contributions to $F_2(s)$ in units of $10^{-6}$.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$s = 0$</th>
<th>$s = (10\text{ GeV})^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-loop QED</td>
<td>1161.41</td>
<td>-265.90</td>
</tr>
<tr>
<td>$e$ loop</td>
<td>10.92</td>
<td>-2.43</td>
</tr>
<tr>
<td>$\mu$ loop</td>
<td>1.95</td>
<td>-0.34</td>
</tr>
<tr>
<td>2-loop QED (mass independent)</td>
<td>-0.42</td>
<td>-0.24</td>
</tr>
<tr>
<td>HVP</td>
<td>3.33</td>
<td>-0.33</td>
</tr>
<tr>
<td>EW</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>total</td>
<td>1177.66</td>
<td>-268.77</td>
</tr>
</tbody>
</table>

- Detector level systematics cancels in asymmetries between left (right) beams.
- Precision $\approx \mathcal{O}(10^{-5})$ or better expected with 50 ab$^{-1}$ of data with 70% polarized beam – orders of magnitude improvement.
- To achieve $\mathcal{O}(10^{-6})$ requires more precise knowledge of $m_\tau$ and $m_{Y(1S)}$ and more statistics
Summary

- e^- polarization upgrade at SuperKEKB would open a unique discovery window with precision electroweak physics
  - Measure the b, charm, tau, muon vector couplings with the highest precision and competitive electron coupling measurement
  - Unique probe of universality at unprecedented precision

- Access tau g-2 at orders of magnitude higher precision than any other method via $F_2(10\text{GeV})$

- Also get significant improvements to LFV, Michel parameters, LFV, EDM
Summary

• Competitive $\sin^2\theta_W$ with measurements at Z-pole (until FCC) but at 10.58 GeV and complementary to Moller and low energy PV
  • test running of couplings
  • probe new physics at TeV scale complementary to LHC
  • probe ‘Dark Sector’

• Applying for US-Japan funds for development of spin rotators at BNL and polarization source

• Build on international partnerships with KEK to create a unique discovery machine
SuperKEKB polarization upgrade

• Aim to install polarization Long Shutdown 2
• Polarization R&D in MEXT KEK Roadmap 2021-26
With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

<table>
<thead>
<tr>
<th>Final State Fermion</th>
<th>SM $g_v^f (M_Z)$</th>
<th>World Average$^1$ $g_v^f$</th>
<th>Chiral Belle $\sigma$ 20 ab$^{-1}$</th>
<th>Chiral Belle $\sigma$ 40 ab$^{-1}$</th>
<th>Chiral Belle $\sigma \sin^2 \Theta_W$ 40 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-quark (eff.=0.3)</td>
<td>-0.3437 ± 0.0001</td>
<td>-0.3220 ±0.0077 (high by 2.8$\sigma$)</td>
<td>0.002 Improve x4</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>c-quark (eff. = 0.15)</td>
<td>+0.1920 ±0.0002</td>
<td>+0.1873 ± 0.0070</td>
<td>0.001 Improve x7</td>
<td>0.001</td>
<td>0.0008</td>
</tr>
<tr>
<td>Tau (eff. = 0.25)</td>
<td>-0.0371 ±0.0003</td>
<td>-0.0366 ± 0.0010</td>
<td>0.001 (similar)</td>
<td>0.0008</td>
<td>0.0003</td>
</tr>
<tr>
<td>Muon (eff. = 0.5)</td>
<td>-0.0371 ±0.0003</td>
<td>-0.03667±0.0023</td>
<td>0.0007 Improve x 3</td>
<td>0.0005</td>
<td>0.0003</td>
</tr>
<tr>
<td>Electron (17nb, eff=0.36)</td>
<td>-0.0371 ±0.0003</td>
<td>-0.03816 ±0.00047</td>
<td>0.0009</td>
<td>0.0006</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

$^1$ Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

$\sin^2 \Theta_W$ - all LEP+SLD measurements combined $WA = 0.23153 \pm 0.00016$

$\sin^2 \Theta_W$ - Chiral Belle combined leptons with 40 ab$^{-1}$ have error $\sim$current WA

**CP violation and electric dipole moment at low energy tau production with polarized electrons**

For polarized beams

\[ P_N^\tau \propto \lambda \gamma \beta^2 \cos \theta_\tau \sin \theta_\tau \frac{m_\tau}{e} \text{Re}(d_\tau^\gamma) \]

Angular asymmetries (\( P_N^\tau \)) are proportional to EDM

\[ A_N^m = \frac{\sigma_L^m - \sigma_R^m}{\sigma_L^m + \sigma_R^m} = \alpha_m \frac{3\pi \gamma \beta}{8(3 - \beta^2)} \frac{2m_\tau}{e} \text{Re}(d_\tau^\gamma) \]

One can also measure \( A \) for \( \tau^+ \) and/or \( \tau^- \)

\[ A_N^{CP} \equiv \frac{1}{2} (A_N^+ + A_N^-) \]
EDM of the $\tau$ Lepton with e- polarized SuperKEKB

Beam polarization substantially improves $\tau$ EDM experimental sensitivity by allowing measurements of the polarization of a single $\tau$, rather than measurements of correlations between two $\tau$ leptons produced in the same event.

The beam polarization upgrade at SuperKEKB furthers experimental sensitivity since the uncertainties in modeling the forward-backward asymmetry in the detector response are independent of beam polarization and will largely cancel.

-> $40\text{ab}^{-1}$ Chiral Belle data with 70% polarization, the sensitivity is

$$|d_{\tau\gamma}| < O(10^{-20})$$

(Statistical error only)

Note: extrapolating statistical error from recent Belle results would give a limit of $\sim 5\times 10^{-19}$ for unpolarized Belle II data with $50\text{ab}^{-1}$
From Denis Epifanov’s talk at Tau2021 on Super Tau Charm Factory: $\tau$ Michel Parameter with polarized e-beam

It would be very exciting to have both projects probing tau sector with polarized e-beams

50ab$^{-1}$ of polarized Belle II data assumed in these studies
Tau Polarization as Beam Polarimeter

\[ P_{\tau^{-}}(\theta, P_e) = -\frac{8G_F s}{4\sqrt{2} \pi \alpha} \text{Re} \left\{ \frac{g_V^l - Q_b g_V^b Y_{1S,2S,3S}(s)}{1 + Q^2_b Y_{1S,2S,3S}(s)} \right\} \left( g_A^\tau \frac{|\bar{p}|}{p^0} + 2g_A^e \frac{\cos \theta}{1 + \cos^2 \theta} \right) + P_e \frac{\cos \theta}{1 + \cos^2 \theta} \]

- Dominant term is the polarization forward-backward asymmetry \( (A_{\text{pol}}^{\text{FB}}) \) whose coefficient is the beam polarization

- Measure tau polarization as a function of \( \theta \) for the separately tagged beam polarization states

- Can expect \( \sim 1/2 \% \) absolute precision of the polarization at the interaction point – includes transport effects, lumi-weighting, stray e\(^+\) polarization

- Method assumes tau neutrino is 100% left handed – motivates validation of this

- Preliminary BaBar results on sensitivity studies are very promising! Systematics < 0.5%
Polarization in SuperKEKB

Hardware needs

1. Low emittance polarized Source
2. Spin rotators
3. Compton polarimeter

Design source photo-cathode
With 4 nC/bunch
20 mm-mrad vertical emittance
50 mm-mrad horizontal emittance
Current focus is on GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

KEK and Hiroshima Groups - work on ILC sources leveraged
Polarization in SuperKEKB

Hardware needs

1. Low emittance polarized Source
2. Spin rotators
3. Compton polarimeter

Design source photo-cathode
With 4 nC/bunch
20 mm-mrad vertical emittance
50 mm-mrad horizontal emittance
Current focus is on GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

KEK and Hiroshima Groups - work on ILC sources leveraged

Y. Peng (UVic)
Polarization in SuperKEKB

Spin Motion of $e^-$ (Co-Moving Frame) in the Linac

- $S_x$
- $S_y$
- $S_z$

Electron source

Injection Point into HER
Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. Spin rotators
3. Compton polarimeter

Use of solenoids and dipoles, plus the quadrupoles (needed for decoupling) on either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups
Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. Spin rotators
3. Compton polarimeter

In preliminary studies, one concept (U. Wienands, ANL) is to use overlapping field magnets which would replace existing bending magnets either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups
Preliminary studies – ANL, TRIUMF, Victoria

Overlapping Field Solenoid-Dipole-Quadrupole Spin Rotator - Uli Wienands, ANL

Yuhao Peng, Victoria

Spin Rotator

Left rotator (L-Rot) is to rotate the vertical spin to the longitudinal direction

Right rotator (R-Rot) is to rotate the longitudinal back to vertical

- replace some existing ring dipoles (send) near the IP with the solenoid-dipole combined function magnets and maintain the original dipole strength to keep the geometry

- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids

U. Wienands, ANL
Preliminary studies – ANL, TRIUMF, Victoria

Simulation Tool

- **Bmad** is an open-source software library (aka toolkit) created/maintained by David Sagan at Cornell University for simulating charged particles and X-rays. Étienne Forest’s “Polymorphic Tracking Code” (**PTC**) is incorporated into it.

- **Tao** is a user-friendly interface to Bmad which gives general purpose simulation, based upon Bmad.

- **Bmad** via the Tao interface is a powerful and user-friendly tool used for viewing lattices, doing Twiss and orbit calculations, and performing nonlinear optimization on lattices.

Using SuperKEKB High Energy Ring lattice (Demin Zhou, KEK)

Original Lattice

<table>
<thead>
<tr>
<th>Model</th>
<th>Design</th>
<th>Model</th>
<th>Design</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>45.530994</td>
<td>45.530994</td>
<td>43.580709</td>
<td>43.580709</td>
<td></td>
</tr>
<tr>
<td>Chrom 1.593588</td>
<td>1.591895</td>
<td>1.622865</td>
<td>1.621568</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J_damp 1.000002</td>
<td>0.999662</td>
<td>1.000002</td>
<td>1.000002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emittance 4.44061E-09 4.44277E-09</td>
<td>5.65367E-13 5.65331E-13</td>
<td>! Damping Partition</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lattice with Rotators after re-matching chromaticity and tunes

<table>
<thead>
<tr>
<th>Model</th>
<th>Design</th>
<th>Model</th>
<th>Design</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>45.530994</td>
<td>45.530994</td>
<td>43.580709</td>
<td>43.580709</td>
<td></td>
</tr>
<tr>
<td>Chrom 1.593588</td>
<td>1.591895</td>
<td>1.622865</td>
<td>1.621568</td>
<td>dQ/(dE/E)</td>
<td></td>
</tr>
<tr>
<td>J_damp 0.984216</td>
<td>0.983532</td>
<td>1.005266</td>
<td>1.005266</td>
<td>! Damping Partition</td>
<td></td>
</tr>
<tr>
<td>Emittance 4.89676E-09 4.89624E-09</td>
<td>3.96631E-12 3.96983E-12</td>
<td>! Meters</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Next steps: now conducting long term tracking studies -> very promising

Yuhao Peng (Victoria)
Preliminary studies – ANL, TRIUMF, Victoria

Spin Motion of $e^-$ (Lab Frame) in the SuperKEKB HER with Spin Rotator Installed

Comparison of Full Lattice

<table>
<thead>
<tr>
<th>Spin Component</th>
<th>Entrance of Rot</th>
<th>IP</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$-0.0000032792024300$</td>
<td>$-0.0000044677361868$</td>
<td>$-0.0000063748934711$</td>
</tr>
<tr>
<td>Y</td>
<td>$0.9999999999802550$</td>
<td>$0.0000026796195603$</td>
<td>$0.999999999793680$</td>
</tr>
<tr>
<td>Z</td>
<td>$-0.0000053600276775$</td>
<td>$0.999999999864290$</td>
<td>$0.000007825194459$</td>
</tr>
</tbody>
</table>

Yuhao Peng, Victoria
Preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions

From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB
Preliminary studies by BINP group

A scheme with restoration of the vertical spin direction in main arcs

HER: $E = 7$ GeV, $v_0 = 15.886$

Vertical spin direction:

Spin direction is vertical in the main part of HER. Then it is rotated to the horizontal plane by the set of two solenoids, which are comprising the $90^\circ$ spin rotator.

From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB
Depolarization lifetime at $E=7.15\text{GeV}$ is $7500\text{s}$ ($\sim 2\text{ hrs}$)

Note: beam is topped-up @ 50Hz continuously (current beam lifetime without top-up $\sim 1\text{hr}$)

From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB
Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. Spin rotators
3. Compton polarimeter

Space is available for laser interaction region and scattered electron detector

LAL Orsay and U. Manitoba groups
Polarization in SuperKEKB

LAL Orsay team (A. Martens, Y. Peinaud, F. Zomer, P. Bambade, F. Le Diberder, K. Trabselsi)  HERA Compton Polarimeter experience

Laser beam polarization control

- Polarization independent Holographic Beam Sampler
- Careful suppression of laser intensity fluctuations
- Use of balanced photodiodes and differential electronics

Example of time dependent measurement at HERA
- Remaining 0.3% fluctuations

- More frequent measurements?
- Modulation of circular polarization to avoid DC fluctuations?
U. Manitoba team (J. Mammei, M. Gericke, W. Deconinck) work on Compton polarimeter at JLab - QWeak and MOLLER – Using HPVMAPs as Compton e- Detector at MOLLER

HVMAPS Beam Test, Fall 2019, DESY

We recently had a beam test of the 8th (2x1 cm²) and 9th generation chip at DESY.

Version 10 will be submitted for production by the end of this year (full 2x2 cm²).

If it performs well, version 11 (2020 submission) will be the production chip we use for MOLLER.

The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

The implementation as a Compton detector is done by the Manitoba group.
### Linac Beam Parameters for KEKB/SuperKEKB

<table>
<thead>
<tr>
<th>Stage</th>
<th>KEKB (final)</th>
<th>Phase-I</th>
<th>Phase-II</th>
<th>Phase-III (interim)</th>
<th>Phase-III (final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
<td>e⁺, e⁻</td>
</tr>
<tr>
<td>Energy</td>
<td>3.5 GeV, 8.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
<td>4.0 GeV, 7.0 GeV</td>
</tr>
<tr>
<td>Stored current</td>
<td>1.6 A, 1.1 A</td>
<td>1.0 A, 1.0 A</td>
<td>–</td>
<td>–</td>
<td>1.8 A, 1.3 A</td>
</tr>
<tr>
<td>Life time (min.)</td>
<td>150</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>primary e⁻ 10</td>
<td>primary e⁻ 8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>–1</td>
<td>1</td>
<td>–0.4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Norm. Emittance</td>
<td>1400</td>
<td>310</td>
<td>1000</td>
<td>130</td>
<td>150/30</td>
</tr>
<tr>
<td></td>
<td>(µrad)</td>
<td></td>
<td></td>
<td>(Hor./Ver.)</td>
<td>(Hor./Ver.)</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.13%</td>
<td>0.13%</td>
<td>0.50%</td>
<td>0.50%</td>
<td>0.16%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch / Pulse</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
<td></td>
<td>25 Hz</td>
<td>25 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Simultaneous top-up</td>
<td>3 rings (LER, HER, PF)</td>
<td>No top-up</td>
<td>Partially</td>
<td>4+1 rings (LER, HER, DR, PF-PF-AR)</td>
<td>4+1 rings (LER, HER, DR, PF-PF-AR)</td>
</tr>
<tr>
<td>injection (PPM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>