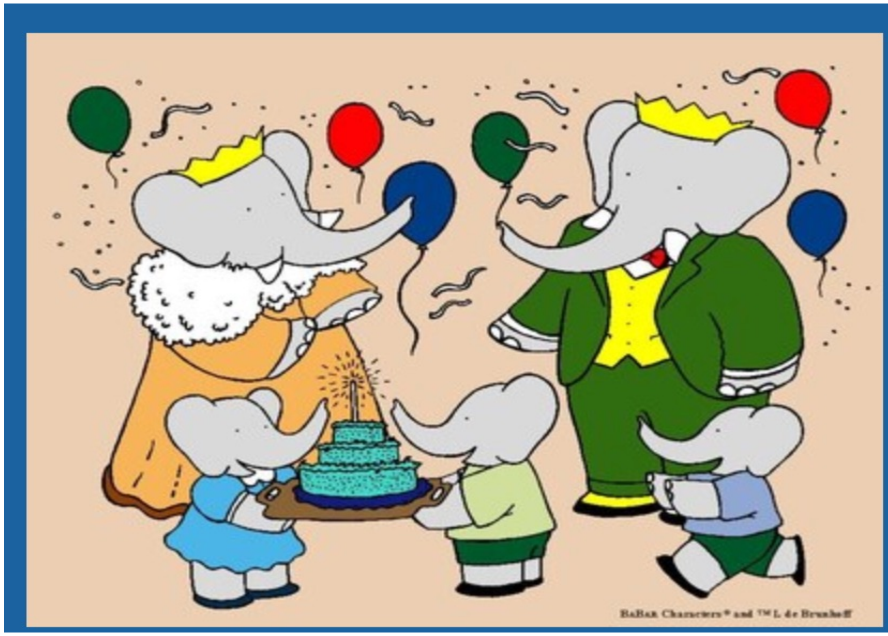

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Flavor Physics Symposium Celebrating BaBar's 30th Anniversary

Chiral Belle:
Upgrading SuperKEKB with e^- Beam Polarization

J. Michael Roney

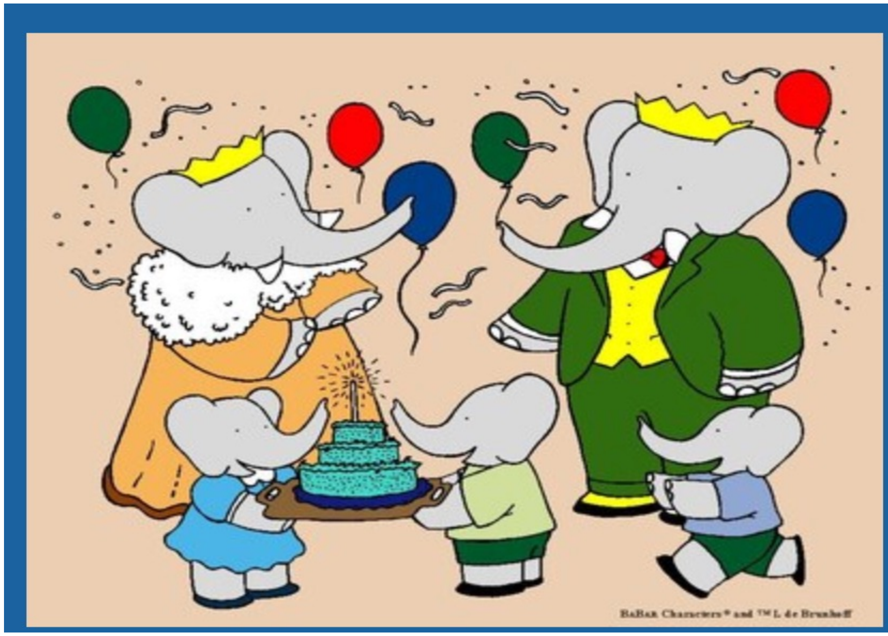
University of Victoria

8 March 2024

On behalf of the

Belle II/SuperKEKB e- Polarization Upgrade Working Group

University of Victoria



Chiral Belle:
Upgrading SuperKEKB with e^- Beam Polarization

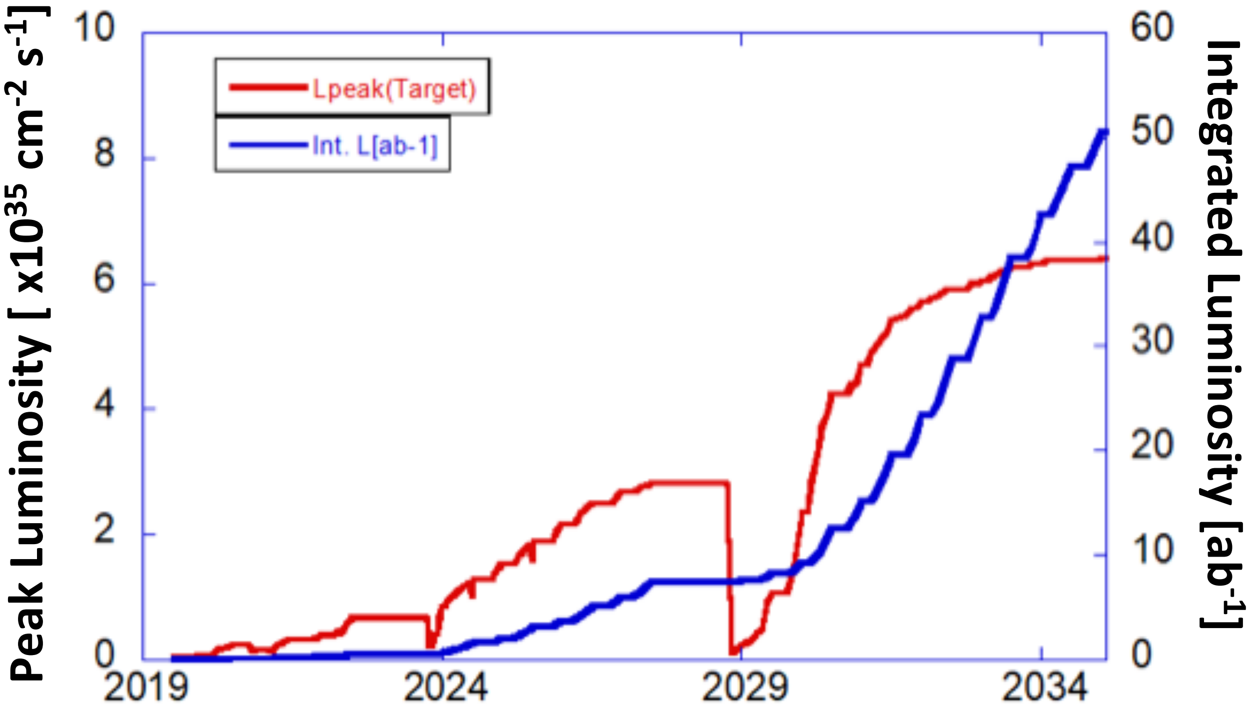
Snowmass White Paper
"Upgrading SuperKEKB with Polarized Electron Beam: Discovery Potential and Proposed Implementation"
arXiv:2205.12847

University
of Victoria

SuperKEKB's HIGH LUMINOSITY drives the rich research program of Belle II and

getting to the design luminosity is our highest priority

SuperKEKB Luminosity Projection



SuperKEKB's HIGH LUMINOSITY drives the rich research program of Belle II and

getting to the design luminosity is our highest priority

FORTUITOUSLY, SuperKEKB's HIGH LUMINOSITY also enables an

entirely new, rich and unique physics program when we

POLARIZE THE ELECTRONS BEAM

SuperKEKB's HIGH LUMINOSITY drives the rich research program of Belle II and

getting to the design luminosity is our highest priority

FORTUITOUSLY, SuperKEKB's HIGH LUMINOSITY also enables an

entirely new, rich and unique physics program when we

POLARIZE THE ELECTRONS BEAM

Data with polarized e^- beam to be collected by Belle II and used simultaneously for conventional non-polarized beam physics program: no negative impact on the existing program

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 Lepton Magnetic Form factor $F_2(10\text{GeV}) \rightarrow \tau$ g-2
- Polarized Beam also provides:
  - Improved precision measurements of τ Michel Parameters, electric dipole moment (EDM)
  - Reduces backgrounds in $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ leading to significantly improved sensitivities
- hadronic studies

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

$$\text{Recall: } g_V^f \text{ gives } \theta_W \text{ in SM} \begin{cases} g_A^f = T_3^f \\ g_V^f = T_3^f - 2Q_f \sin^2\theta_W \end{cases}$$

as well as light quarks

T_3 = -0.5 for charged leptons and D-type quarks
+05 for neutrinos and U-type quarks

‘Chiral Belle’ → Left-Right Asymmetries

- Measure difference between cross-sections with left-handed beam electrons and right-handed beam electrons
- Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

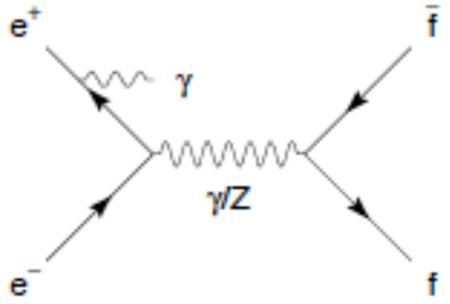
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

At 10.58 GeV, polarized e^- beam yields product of the neutral current axial-vector coupling of the electron & vector coupling of the final-state fermion via Z-γ interference:

for s-channel Born:

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

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$



With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

Final State Fermion	SM A_{LR}	Relative Error (statistical error & sys from 0.5% P_e) For 40 ab^{-1}
b-quark (selection eff.=0.3)	-0.0200 ±0.0001	0.5%
c-quark (eff. = 0.3)	+0.00546 ±0.00003	0.5%
tau (eff. = 0.25)	-0.00064 ±.000015	2.4%
muon (eff. = 0.5)	-0.00064 ±.000009	1.5%
Electron (barrel) (eff. = 0.36)	+0.00015 ±.000003	2.0%

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 ± 0.00016

With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

Final State Fermion	SM g_V^f (M_Z)	World Average[1] g_V^f	Chiral Belle σ 20 ab^{-1}	Chiral Belle σ 40 ab^{-1}	Chiral Belle σ $\sin^2\Theta_W$ 40 ab^{-1}
b-quark (eff.=0.3)	-0.3437 ± .0001	-0.3220 ±0.0077 (high by 2.8σ)	0.002 Improve x4	0.002	0.003
c-quark (eff. = 0.3)	+0.1920 ±.0002	+0.1873 ± 0.0070	0.001 Improve x7	0.001	0.0008
Tau (eff. = 0.25)	-0.0371 ±.0003	-0.0366 ± 0.0010	0.001 (similar)	0.0008	0.0004
Muon (eff. = 0.5)	-0.0371 ±.0003	-0.03667±0.0023	0.0007 Improve x 3	0.0005	0.0003
Electron (17nb, eff=0.36)	-0.0371 ±.0003	-0.03816 ±0.00047	0.0009	0.0006	0.0003

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

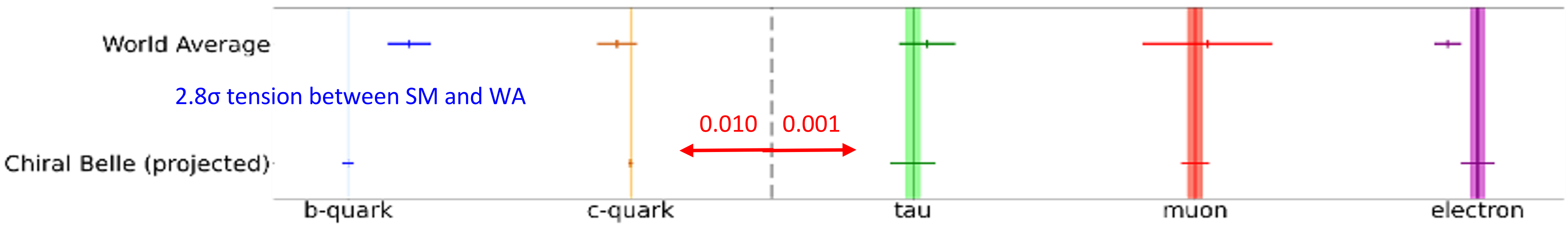
$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

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

Precision electroweak measurements

Fermion	g_V^f (Standard Model)	g_V^f (World Average)	$\sigma(g_V^f)$ **(Chiral Belle 40ab^{-1})**
b-quark	**-0.3437 ± 0.0001**	**-0.3220 ± 0.0077**	**0.002 (4 x improvement)**
c-quark	**0.1920 ± 0.0002**	**0.1873 ± 0.0070**	**0.001 (7 x improvement)**
Tau	**-0.0371 ± 0.0003**	**-0.0366 ± 0.0010**	**0.0008**
Muon	**-0.0371 ± 0.0003**	**-0.03667 ± 0.0023**	**0.0005 (4 x improvement)**
Electron	**-0.0371 ± 0.0003**	**-0.03816 ± 0.00047**	**0.0006**

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



2.8σ tension between SM and WA

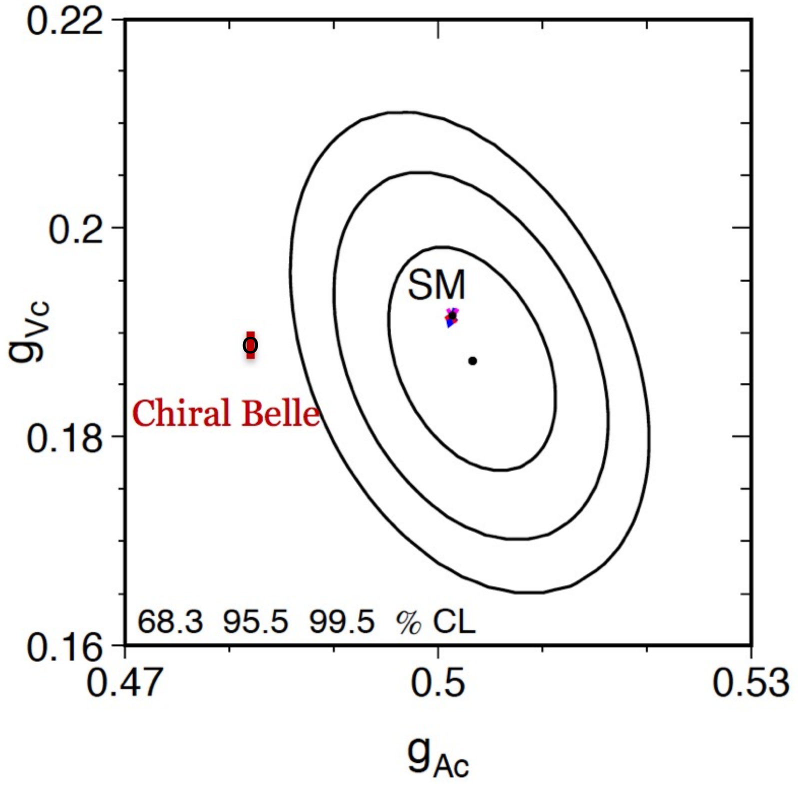
0.010 0.001

Chiral Belle probes both high and low energy scales

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

c-quark:

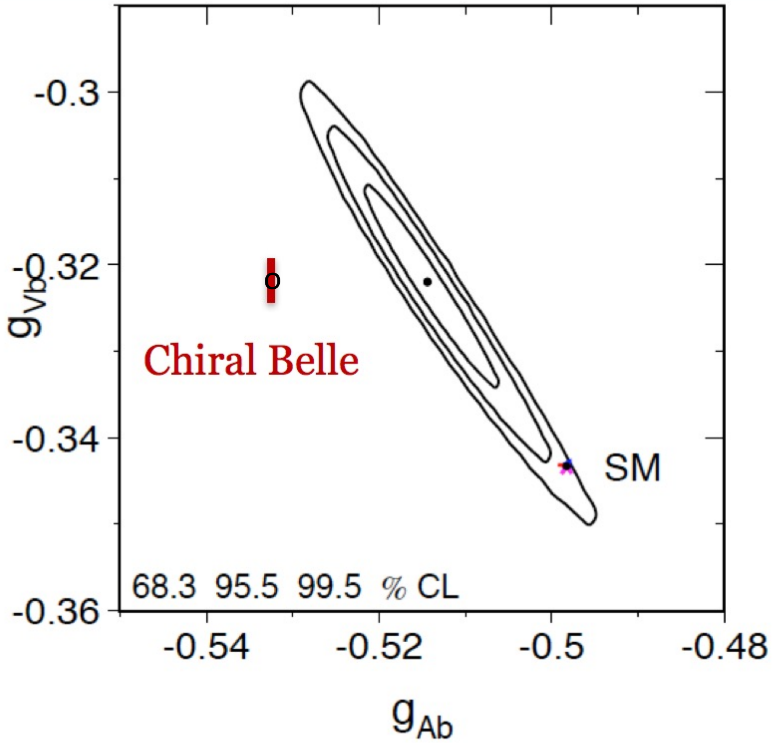
Chiral Belle ~7 times more precise



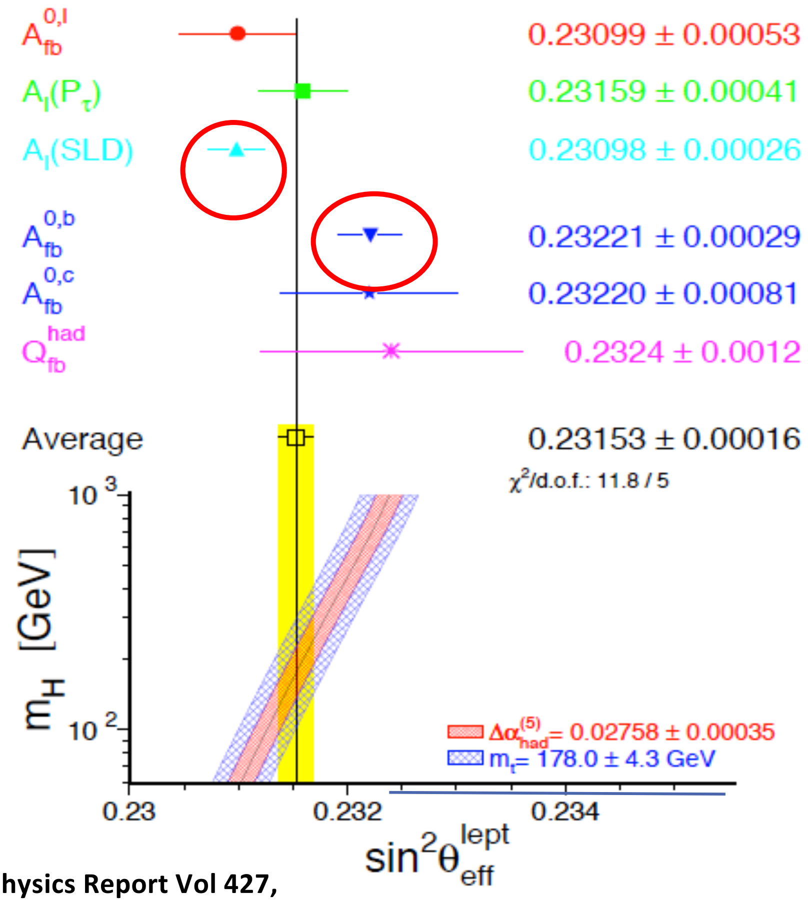
b-quark:

Chiral Belle ~4 times more precise

with 20 ab^{-1}



Existing tension in data on the Z-Pole



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

3.2σ tension between A_{LR} (SLC) and $A^{0,b}_{fb}$(LEP)

LHC precision electroweak program limited by strong interaction hadronization effects in Z → b-quark pairs (Physics Report 2006)
But Chiral Belle is at B-meson pair production threshold, so not limited by this

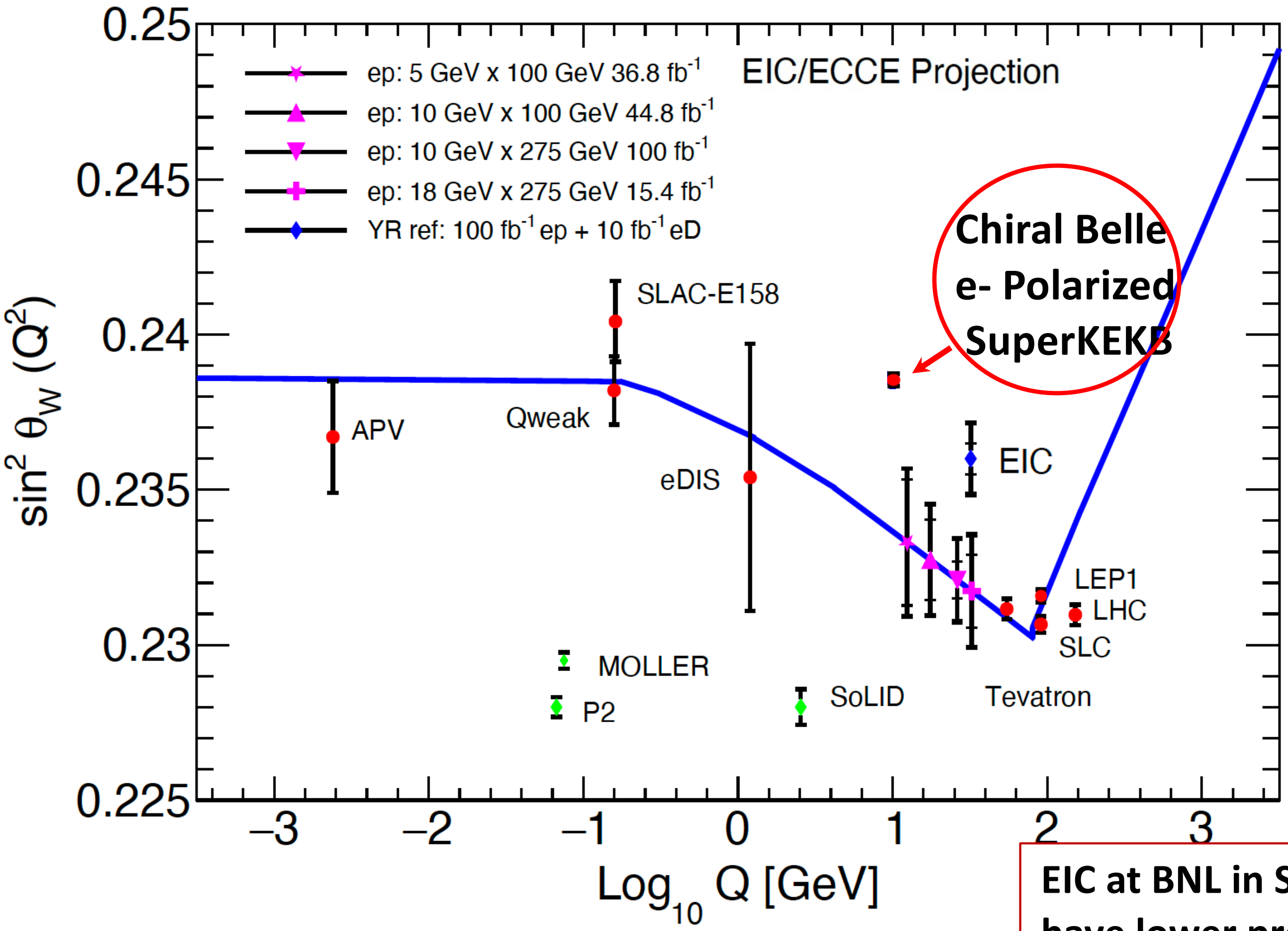
Chiral Belle unique position to resolve whether this tension is early sign of e:b universality violation signally New Physics or a fluctuation

20ab^{-1} @ Chiral Belle gives Highest precision neutral-current universality measurements by many factors (e.g. Chiral Belle b-quark to c-quark universality measurement is >14x more precise than combined World Average)

Precision weak mixing angle $\sin^2\theta_W$

same precision as at Z^0-pole measured at CERN (LEP) and SLAC (SLD)

but at 10GeV probes energy scaling of $\sin^2\theta_W$ making Chiral Belle a UNIQUE precision probe of New Physics in dark sector with e, μ, τ, c- and b-quarks



Chiral Belle
e- Polarized
SuperKEKB

Figure Adapted from *Phys Rev D 106, 016006 (2022)*
(used in EIC Snowmass Whitepaper *arXiv:2203.13199v2*)
using data from PDG 2022 EW review (Erler&Freitas)

Chiral Belle:
σ = 0.00018 with 40ab^{-1}
Using only clean leptonic states (common <Pol> systematic included)

- **Precision probe of running of $\sin^2\theta_W$**
- **Being away from Z-pole opens NP sensitivities not available at the pole**

MOLLER at JLab complementary as they are at lower energy but only probes electron couplings
***cf* Chiral Belle: e, μ, τ, c- & b-quarks**

EIC at BNL in SuperKEKB energy range, but EIC will have lower precision and only for couplings involving 1st generation fermions $\sigma_{\sin 2\theta W}$ (EIC) = 0.0012
***cf* 0.0002 @ Chiral Belle**

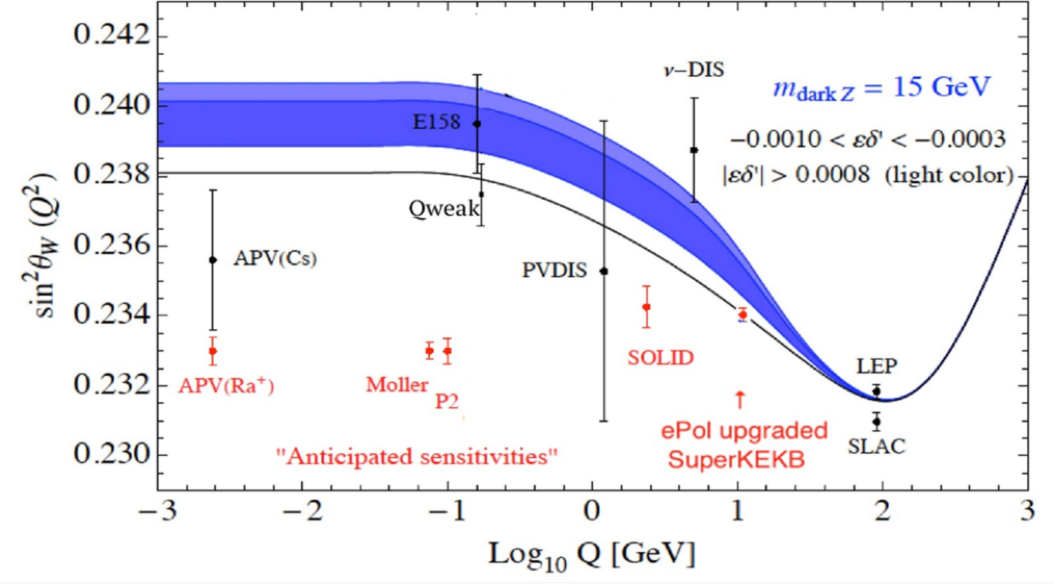
Staging of Chiral Belle Precision electroweak measurements

Fermion	g_V^f (SM)	g_V^f (WorldAve)	$\sigma(g_V^f)$ **Chiral Belle** **0.5ab^{-1}**	$\sigma(g_V^f)$ **Chiral Belle** **1ab^{-1}**	$\sigma(g_V^f)$ **Chiral Belle** **5ab^{-1}**	$\sigma(g_V^f)$ **Chiral Belle** **10ab^{-1}**
b-quark	-0.3437 ± 0.0001	-0.3220 ± 0.0077	0.0026 3x improvement over WA	0.0022	0.0018 4x improvement over WA	0.0018 4x improvement over WA
c-quark	0.1920 ± 0.0002	0.1873 ± 0.0070	0.005	0.0036 2x improvement over WA	0.0018	0.0014 5x improvement over WA
Tau	-0.0371 ± 0.0003	-0.0366 ± 0.0010	0.0069	0.0049	0.0022	0.0015
Muon	-0.0371 ± 0.0003	-0.03667 ± 0.0023	0.0043	0.0031	0.0014	0.0010 2x improvement over WA
Electron	-0.0371 ± 0.0003	-0.03816 ± 0.00047	0.0055	0.0039	0.0017	0.0012

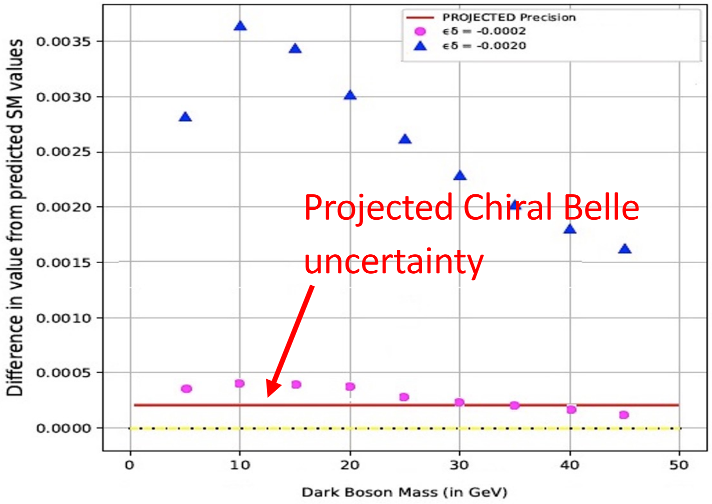
Upgrading SuperKEKB with e- Polarized Beams:
Chiral Belle → unique probe of Dark Sector

Running of $\sin^2\Theta_W$: PV window to the Dark Sector

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



Differences between SM and two benchmark scenarios of dark Z



- **Adapted from Fig. 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015.**
- **Red bar shows expected ±1 sigma uncertainty 0.00018 with 40 ab^{-1} at Chiral Belle**
- **Also sensitive to parity violation induced by exchange of heavy particles e.g. a hypothetical TeV-scale Z' boson, which if couples only to leptons will be produced @ Belle II but not in pp collisions**
- **Separately sensitive to e, μ, τ, c, b**

Chiral Belle physics broader program includes:

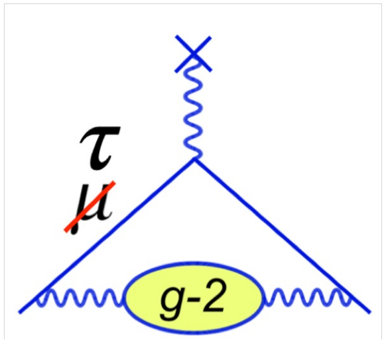
- **Tau Lepton Magnetic Form factor F_2(10GeV) → τ g-2**
- **τ electric dipole moment (EDM) – can reach 10^{-20} ecm level**
- **Improved precision measurements of τ Michel Parameters**
- **e^- beam polarization can be used to reduce backgrounds in $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.**
- **Polarized e+e- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation in QCD**

Magnetic dipole moment of τ lepton

$$\boxed{a_\ell = (g_\ell - 2)/2}$$

Tensions in anomalous magnetic moment of muon…

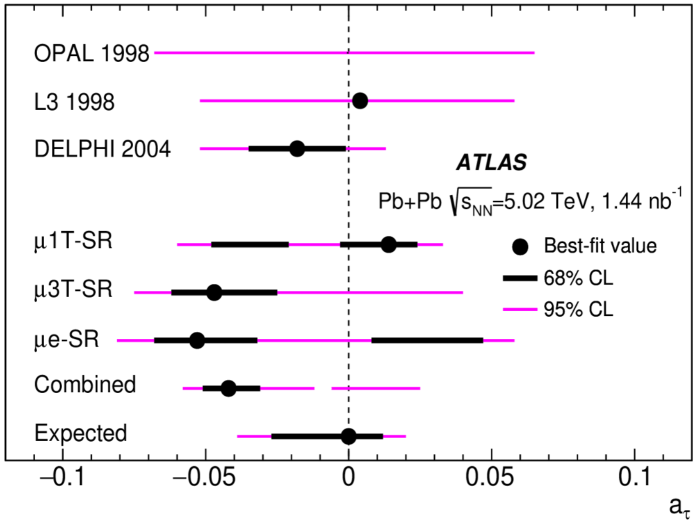
Expectation from Minimal flavor violation:



$$a_\tau^{\mathrm{BSM}} \sim a_\mu^{\mathrm{BSM}} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 10^{-6}$$

Current bound in tau ~ $\mathcal{O}(10^{-2})$

Chiral Belle reach ~ $\mathcal{O}(10^{-5})$ with 50ab^{-1}



e-Print: 2204.13478 [hep-ex]
ATLAS Collaboration

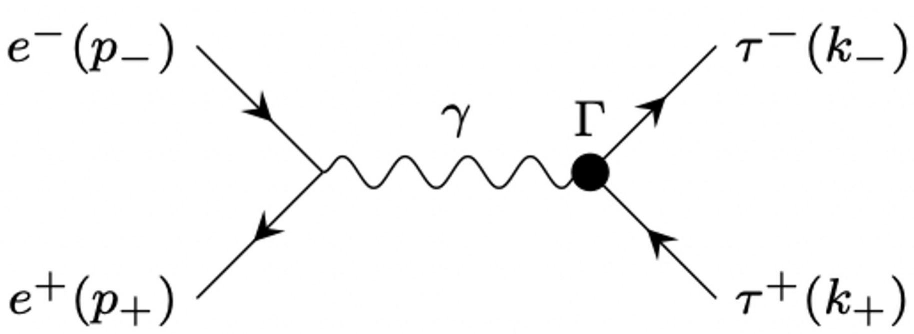
See also

Quentin Buat – ATLAS tau g-2 talk at Tau 2023

Paul Bühler – ALICE tau g-2 talk at Tau 2023

Gabriel González-Springberg – tau g-2 talk at Tau 2023

Effective field theory approach to τ-pair production



$$\Gamma^\mu = \underbrace{F_1\left(q^2\right)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2\left(q^2\right)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3\left(q^2\right)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

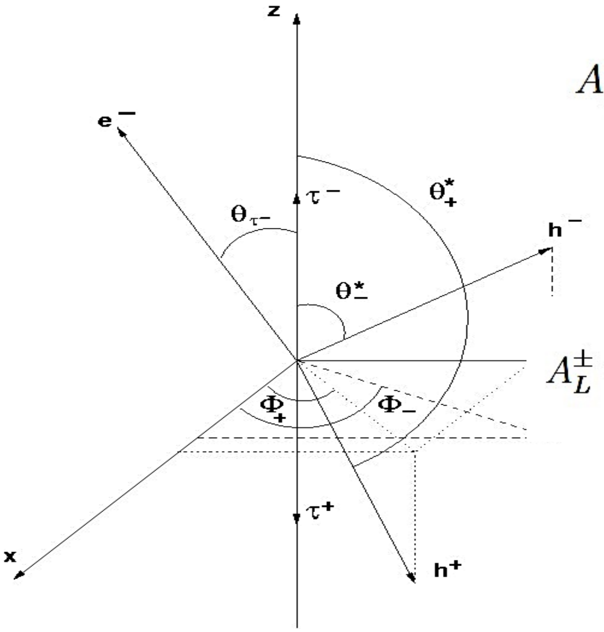
- $F_1\left(q^2\right)$, $F_2\left(q^2\right)$ are called the Dirac and Pauli; $F_1(0) = 1$; $F_2(0) = a_\tau$
- $g = 2\cdot\left[F_1(0) + F_2(0)\right] = 2 + 2F_2(0)$ $d_\tau^\gamma = \frac{e}{2m_\tau}\cdot F_3(0)$

Leading term:

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

"Schwinger term"

Magnetic dipole moment of τ lepton



$$A_T^{\pm} = \frac{1}{2\sigma}\left[\int_{-\pi/2}^{\pi/2}\left(\left(\frac{d\sigma^{R_e}}{d\phi_\pm}\right) - \left(\frac{d\sigma^{L_e}}{d\phi_\pm}\right)\right) d\phi_\pm - \int_{\pi/2}^{3\pi/2}\left(\left(\frac{d\sigma^{R_e}}{d\phi_\pm}\right) - \left(\frac{d\sigma^{L_e}}{d\phi_\pm}\right)\right) d\phi_\pm\right]$$

$$A_L^{\pm} = \frac{1}{2\sigma}\left[\int_0^1 dz_\pm^*\left(\int_0^1 dz\,(A_{RL}) - \int_{-1}^0 dz\,(A_{RL})\right) - \int_{-1}^0 dz_\pm^*\left(\int_0^1 dz\,(A_{RL}) - \int_{-1}^0 dz\,(A_{RL})\right)\right]$$

$$A_{RL} = \frac{d^2\sigma^{R_e}}{dz_\pm^* dz} - \frac{d^2\sigma^{L_e}}{dz_\pm^* dz}$$

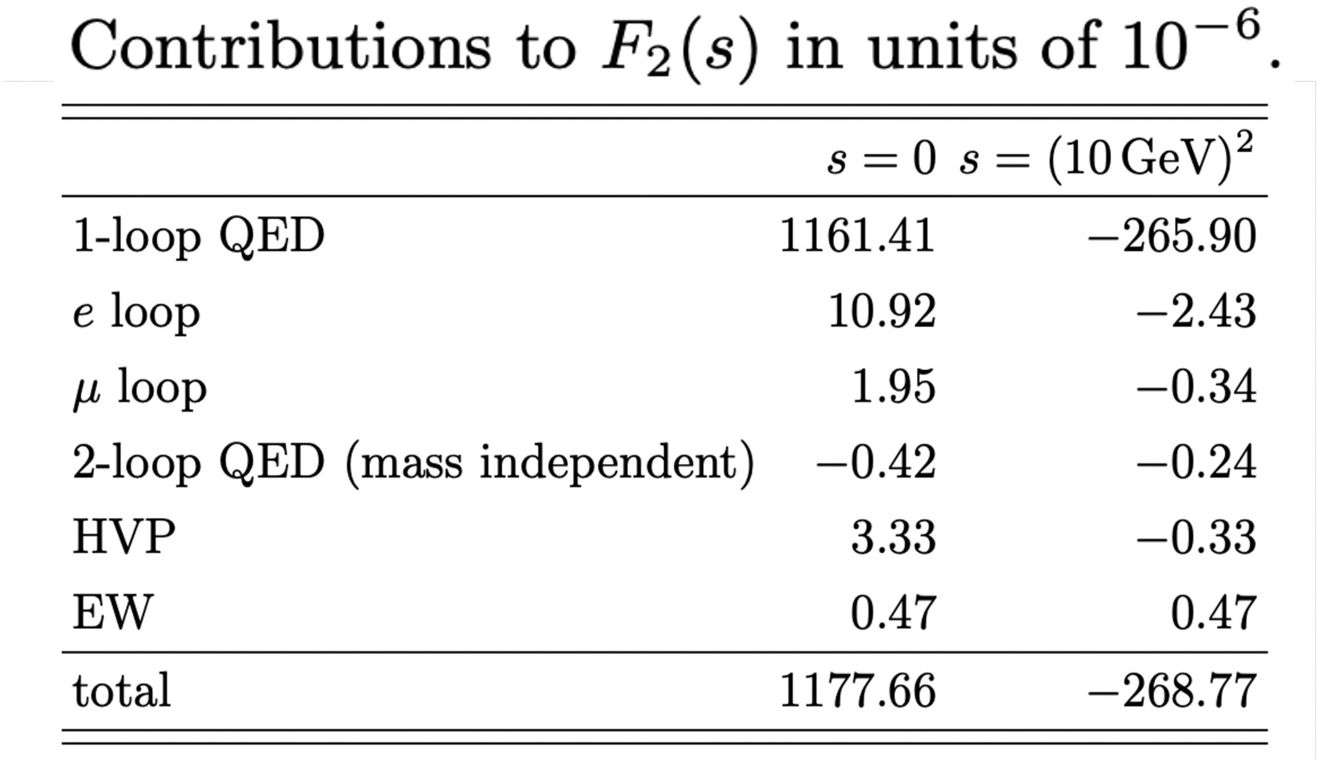
$$\mathrm{Re}(F_2^{\mathrm{eff}}) = \mp\frac{8(3-\beta^2)}{3\pi\gamma\beta^2\alpha_\pm}\left(A_T^{\pm} - \frac{\pi}{2\gamma}A_L^{\pm}\right)$$

requires precision E_{cm} & m_τ for F_1 cancellation

J. Bernabeu, G. A. Gonzalez-Sprinberg, J. Papavassiliou, and J. Vidal, Nucl. Phys. B 790, 160 (2008), arXiv:0707.2496
J. Bernabeu, G. A. Gonzalez-Sprinberg, and J. Vidal, JHEP 01, 062 (2009), arXiv:0807.2366

Magnetic dipole moment of τ lepton

Crivellin, Hoferichter, Roney *Phys.Rev.D* 106 (2022) 9, 093007



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

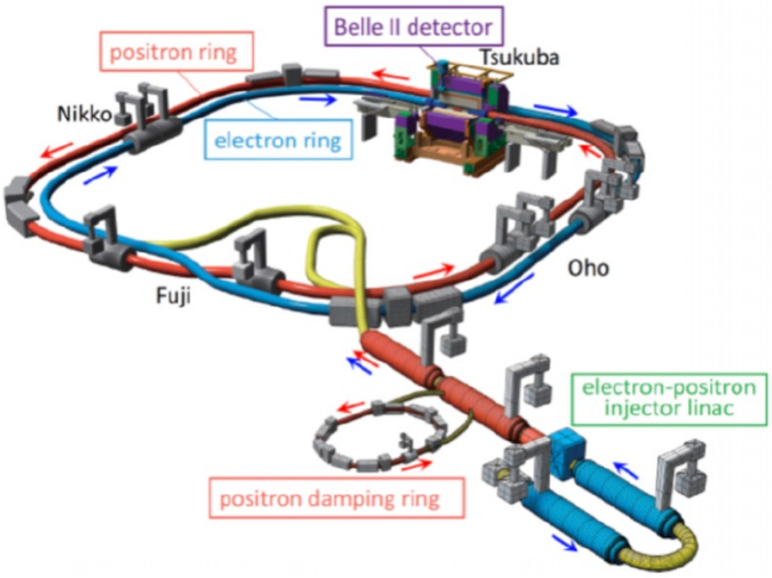
	$s=0$	$s=(10\,\mathrm{GeV})^2$
1-loop QED	1161.41	−265.90
e loop	10.92	−2.43
μ loop	1.95	−0.34
2-loop QED (mass independent)	−0.42	−0.24
HVP	3.33	−0.33
EW	0.47	0.47
total	1177.66	−268.77

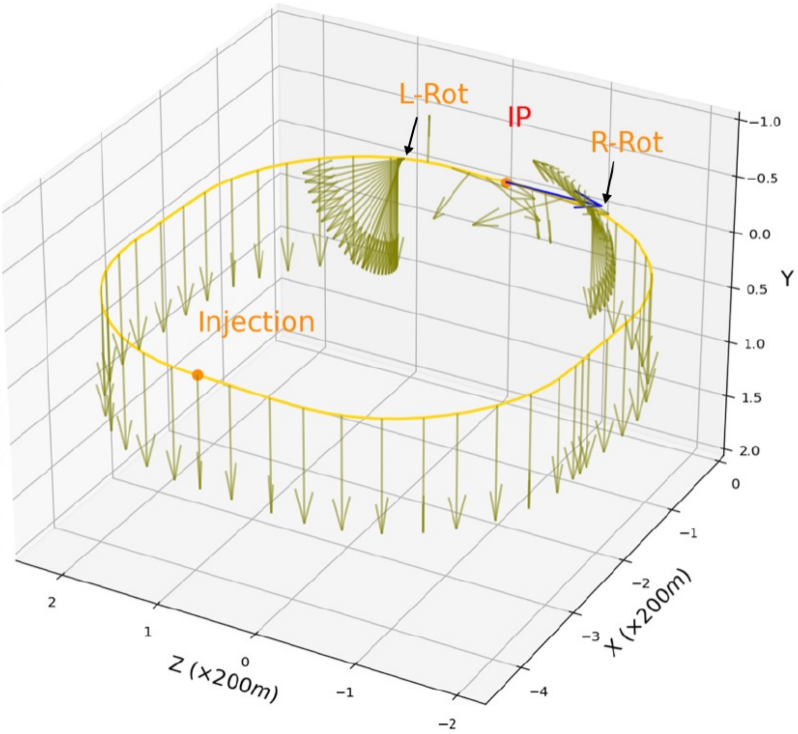
- Detector level systematics cancels in asymmetries between left (right) beams.
- Precision $\simeq \mathcal{O}(10^{-5})$ or better expected with 50 ab^{-1} of data with polarized beam.
- 1000 x more precise than current limits
- Approaches the precision regime in tau that starts to be sensitive to Minimal Flavour Violation equivalent of muon g-2 anomaly

e- beam polarization in SuperKEKB

- Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment) producing longitudinal electron spins at source
- Electron helicity would be changed for trains of bunches by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)
- Inject transversely (vertically) polarized electrons into the High Energy Ring (HER) - needs spin rotator just after photocathode source, e.g. Wien Filter
- Rotate spin to longitudinal before IP, and then back to vertical after IP using solenoidal and dipole fields – requires Spin Rotators
- 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

e- beam polarization in SuperKEKB





Polarization in SuperKEKB

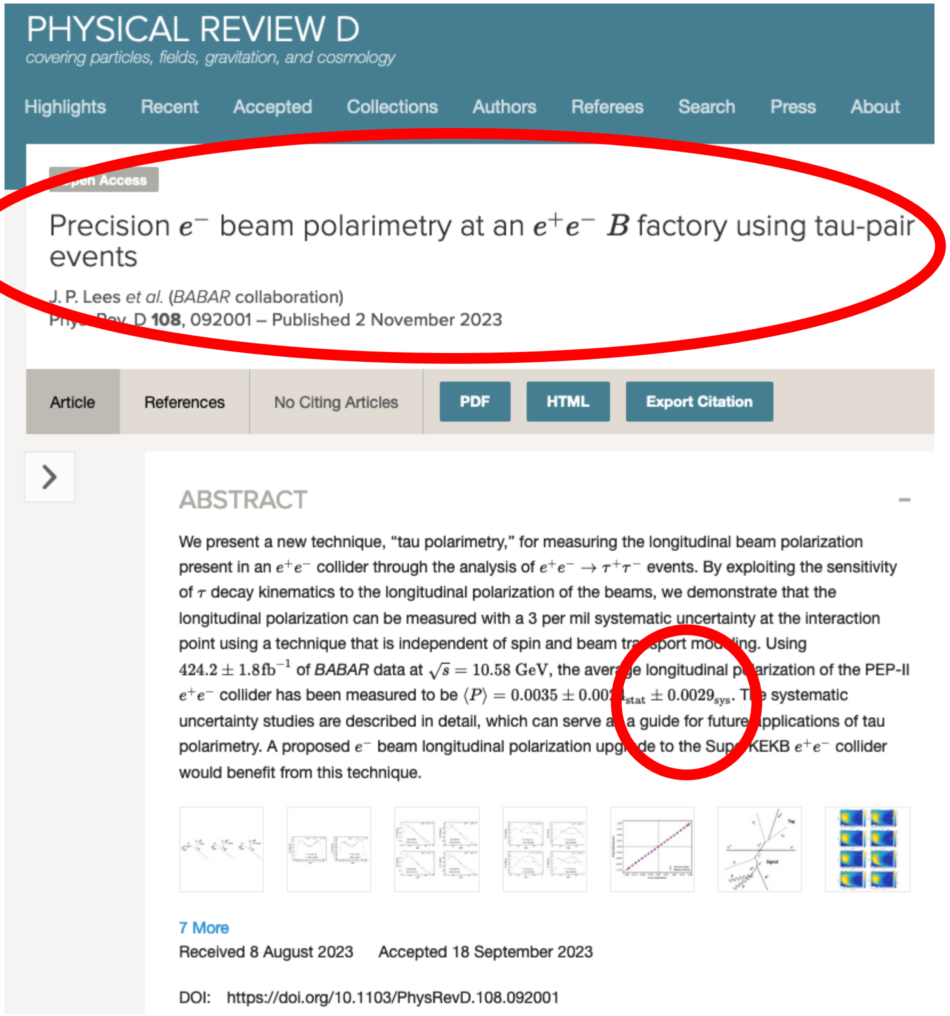
- These precision measurements require highest luminosity possible
- Polarized source not expected to reduce luminosity
- Spin rotators might affect luminosity if not carefully designed to minimize couplings between vertical and horizontal planes
    - Higher order and chromatic effects have to be considered in the design to ensure luminosity is not degraded

e- beam polarization in SuperKEKB

- Requires highest SuperKEKB luminosity AND e- beam polarization
- Source R&D highly synergistic with other international efforts, e.g. EIC
- Requires spin rotators in HER that do not reduce the luminosity (i.e. transparent to the lattice) – high luminosity is required for Chiral Belle
- Requires Precision measurement of polarization (0.005 precision needed)

Beam Polarization: Can be measured to < 0.005

BABAR paper



PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

Precision e^- beam polarimetry at an e^+e^- B factory using tau-pair events

J. P. Lees *et al.* (*BABAR* collaboration)

Phys. Rev. D **108**, 092001 – Published 2 November 2023

ABSTRACT

We present a new technique, "tau polarimetry," for measuring the longitudinal beam polarization present in an e^+e^- collider through the analysis of $e^+e^- \to \tau^+\tau^-$ events. By exploiting the sensitivity of τ decay kinematics to the longitudinal polarization of the beams, we demonstrate that the longitudinal polarization can be measured with a 3 per mil systematic uncertainty at the interaction point using a technique that is independent of spin and beam transport modeling. Using $424.2 \pm 1.8 \mathrm{fb}^{-1}$ of *BABAR* data at $\sqrt{s} = 10.58$ GeV, the average longitudinal polarization of the PEP-II e^+e^- collider has been measured to be $\langle P \rangle = 0.0035 \pm 0.0024_{\mathrm{stat}} \pm 0.0029_{\mathrm{sys}}$. The systematic uncertainty studies are described in detail, which can serve as a guide for future applications of tau polarimetry. A proposed e^- beam longitudinal polarization upgrade to the SuperKEKB e^+e^- collider would benefit from this technique.

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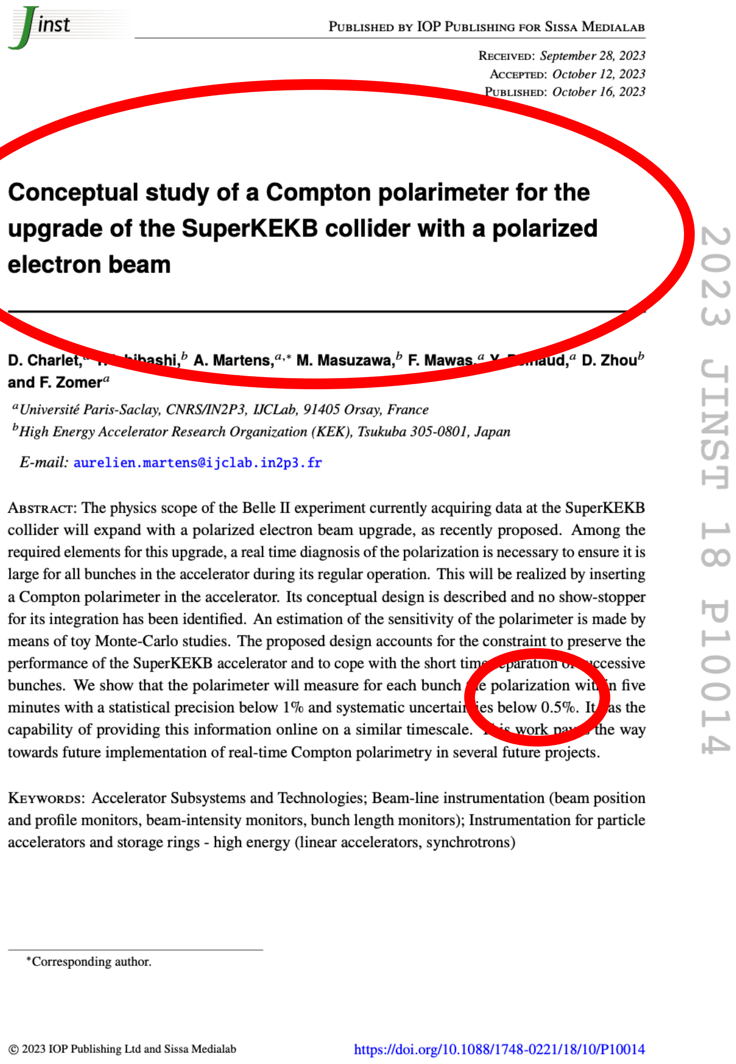
DOI: https://doi.org/10.1103/PhysRevD.108.092001



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Conceptual study of a Compton polarimeter for the upgrade of the SuperKEKB collider with a polarized electron beam

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ABSTRACT: The physics scope of the Belle II experiment currently acquiring data at the SuperKEKB collider will expand with a polarized electron beam upgrade, as recently proposed. Among the required elements for this upgrade, a real time diagnosis of the polarization is necessary to ensure it is large for all bunches in the accelerator during its regular operation. This will be realized by inserting a Compton polarimeter in the accelerator. Its conceptual design is described and no show-stopper for its integration has been identified. An estimation of the sensitivity of the polarimeter is made by means of toy Monte-Carlo studies. The proposed design accounts for the constraint to preserve the performance of the SuperKEKB accelerator and to cope with the short time separation of successive bunches. We show that the polarimeter will measure for each bunch the polarization within five minutes with a statistical precision below 1% and systematic uncertainties below 0.5%. It has the capability of providing this information online on a similar timescale. This work paves the way towards future implementation of real-time Compton polarimetry in several future projects.

KEYWORDS: Accelerator Subsystems and Technologies; Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)

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[*] Corresponding author.

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2023 JINST 18 P10014

Tau Beam Polarimetry (*BABAR* paper): :
e- Polarization be measured to < 0.005

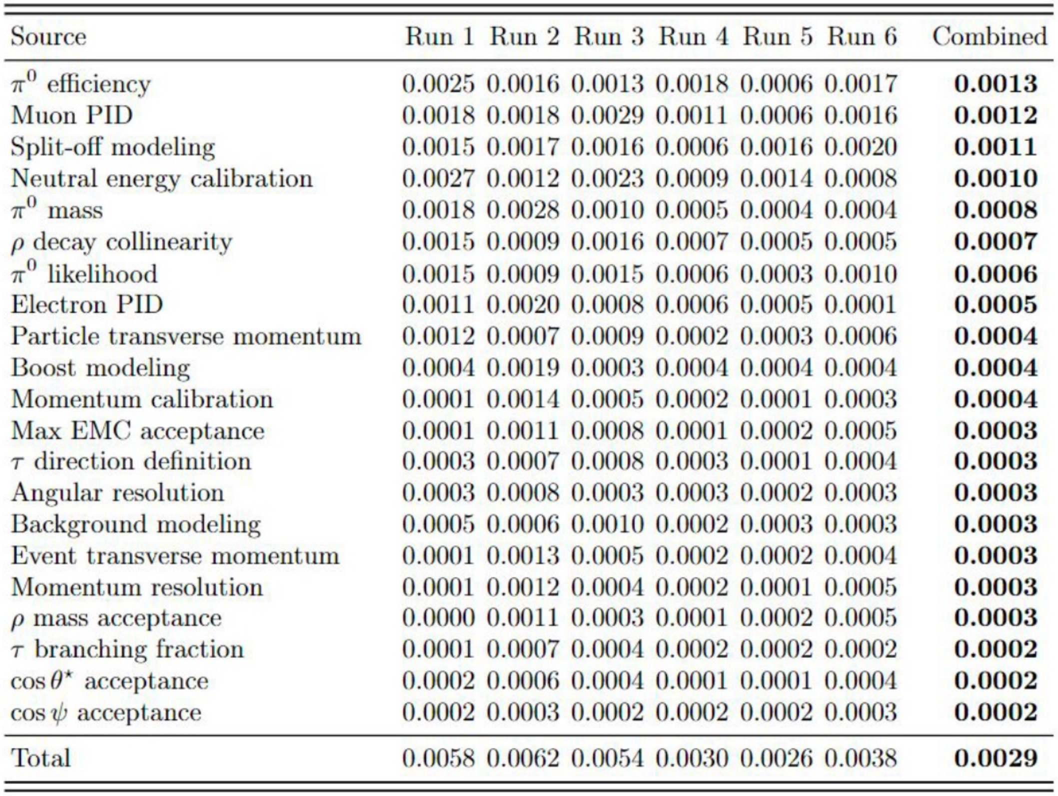
Full Measurement

- Performing the measurement on the full 424.2 fb^{-1}

Sample	Luminosity (fb^{-1})	Average Polarization
Run 1	20.4	0.0062±0.0157
Run 2	61.3	-0.0004±0.0090
Run 3	32.3	0.0048±0.0083
Run 4	99.6	-0.0114±0.0071
Run 5	132.3	-0.0040±0.0063
Run 6	78.3	0.0157±0.0082
Total	**424.2**	**0.0035±0.0024**

- Final measurement:

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} + 0.0029_{\text{sys}}$$

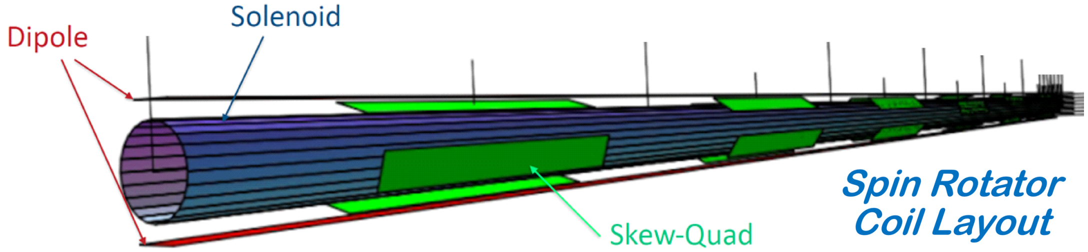


Source	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Combined
π^0 efficiency	0.0025	0.0016	0.0013	0.0018	0.0006	0.0017	**0.0013**
Muon PID	0.0018	0.0018	0.0029	0.0011	0.0006	0.0016	**0.0012**
Split-off modeling	0.0015	0.0017	0.0016	0.0006	0.0016	0.0020	**0.0011**
Neutral energy calibration	0.0027	0.0012	0.0023	0.0009	0.0014	0.0008	**0.0010**
π^0 mass	0.0018	0.0028	0.0010	0.0005	0.0004	0.0004	**0.0008**
ρ decay collinearity	0.0015	0.0009	0.0016	0.0007	0.0005	0.0005	**0.0007**
π^0 likelihood	0.0015	0.0009	0.0015	0.0006	0.0003	0.0010	**0.0006**
Electron PID	0.0011	0.0020	0.0008	0.0006	0.0005	0.0001	**0.0005**
Particle transverse momentum	0.0012	0.0007	0.0009	0.0002	0.0003	0.0006	**0.0004**
Boost modeling	0.0004	0.0019	0.0003	0.0004	0.0004	0.0004	**0.0004**
Momentum calibration	0.0001	0.0014	0.0005	0.0002	0.0001	0.0003	**0.0004**
Max EMC acceptance	0.0001	0.0011	0.0008	0.0001	0.0002	0.0005	**0.0003**
τ direction definition	0.0003	0.0007	0.0008	0.0003	0.0001	0.0004	**0.0003**
Angular resolution	0.0003	0.0008	0.0003	0.0003	0.0002	0.0003	**0.0003**
Background modeling	0.0005	0.0006	0.0010	0.0002	0.0003	0.0003	**0.0003**
Event transverse momentum	0.0001	0.0013	0.0005	0.0002	0.0002	0.0004	**0.0003**
Momentum resolution	0.0001	0.0012	0.0004	0.0002	0.0001	0.0005	**0.0003**
ρ mass acceptance	0.0000	0.0011	0.0003	0.0001	0.0002	0.0005	**0.0003**
τ branching fraction	0.0001	0.0007	0.0004	0.0002	0.0002	0.0002	**0.0002**
$\cos\theta^\star$ acceptance	0.0002	0.0006	0.0004	0.0001	0.0001	0.0004	**0.0002**
$\cos\psi$ acceptance	0.0002	0.0003	0.0002	0.0002	0.0002	0.0003	**0.0002**
Total	0.0058	0.0062	0.0054	0.0030	0.0026	0.0038	**0.0029**

https://doi.org/10.1103/PhysRevD.108.092001

Caleb Miller: Tau 2023 Conference

Compact spin rotator



Follows Uli Wienands's (Argonne National Laboratory) idea and direction:

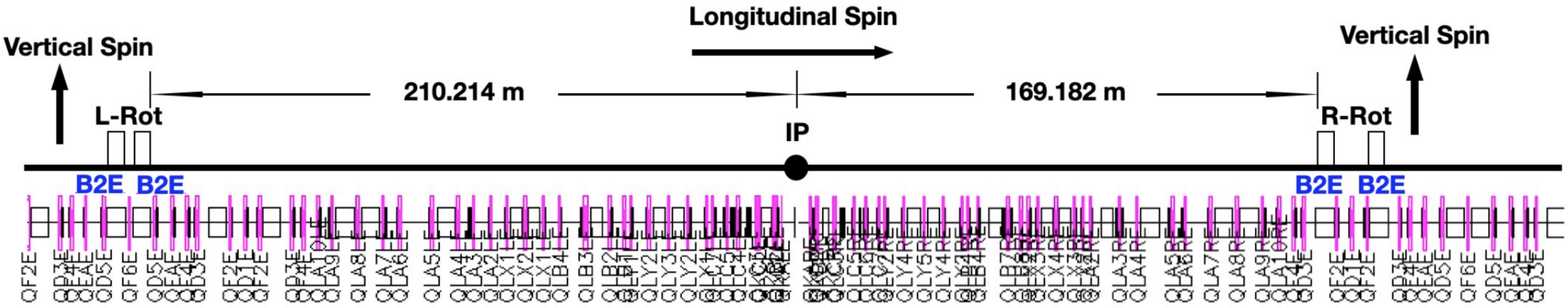
- **Replace some existing ring dipoles on both sides of the IP with the dipole-solenoid combined function magnets and keep the original dipole strength to preserve the machine geometry**
- **Avoids repositioning of other magnets in the ring**
- **Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids**

Original machine can be recovered by turning off solenoid and skew-quadrupole fields + retune with only the dipoles

(BNL expertise in construction of direct wind magnets suitable for these magnets)

Compact spin rotator

Y. Peng (UVic) with Uli Wienands (ANL)



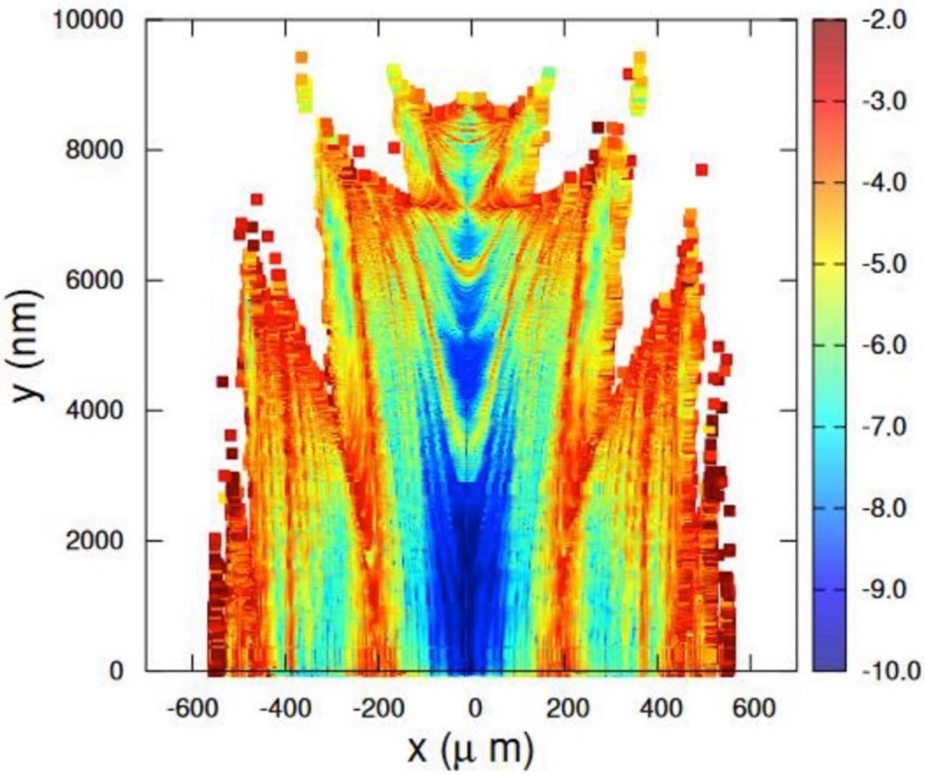
- Left Rotator (L-Rot) rotates the spin from the vertical to the horizontal plane
- Right Rotator (R-Rot) rotates the spin back to the vertical direction
- 4 **B2E** dipoles (using SAD lattice naming convention for HER) shown above to be replaced with the spin rotator magnets

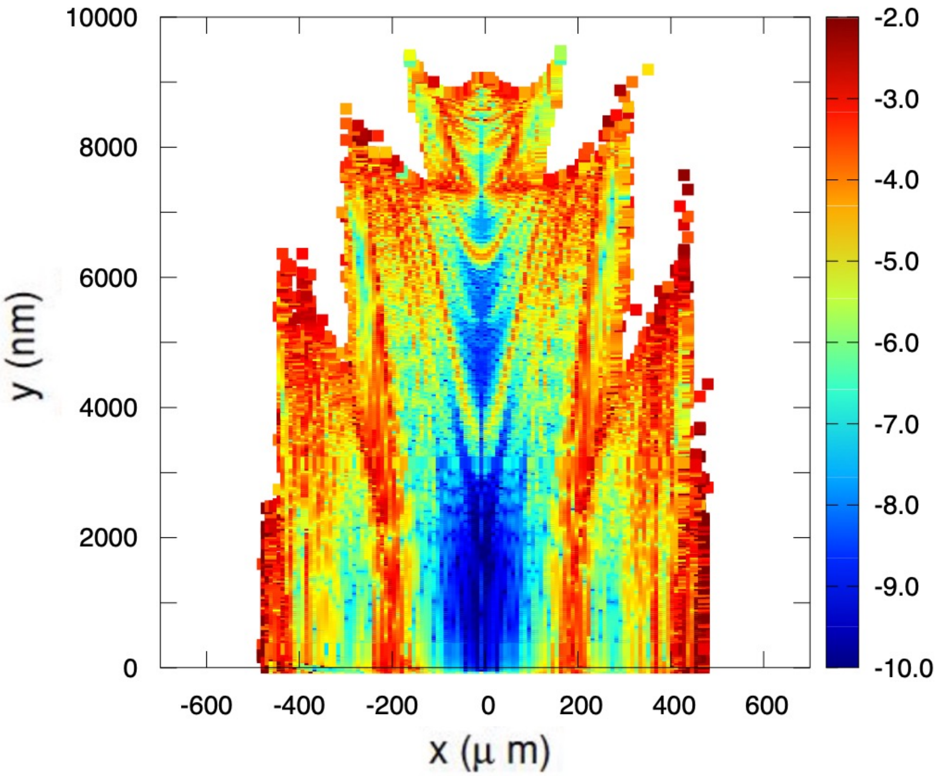
Compact spin rotator

Frequency Map Analysis (FMA)

dynamic aperture studies using BMAD – show no large changes

Noah Tessema (UVic) advised by D. Zhou (KEK), U. Wienands (ANL)


Original HER Lattice


HER Lattice with Compact Spin Rotator

Compact spin rotator

Long Term Tracking(LTT): Explores *non-linear* features of beam lifetime and polarization lifetime with radiation damping and radiation fluctuations/quantum excitation

BMAD LTT studies [N. Tessema (UVic) + U. Wienands (ANL)] of Peng-Wienand spin rotator solution after improving the dipole model in BMAD deployed for these compact magnets

Conclusion:

- Beam is stable with compact spin rotators (5 million turns with 20 particles – no lost particles)

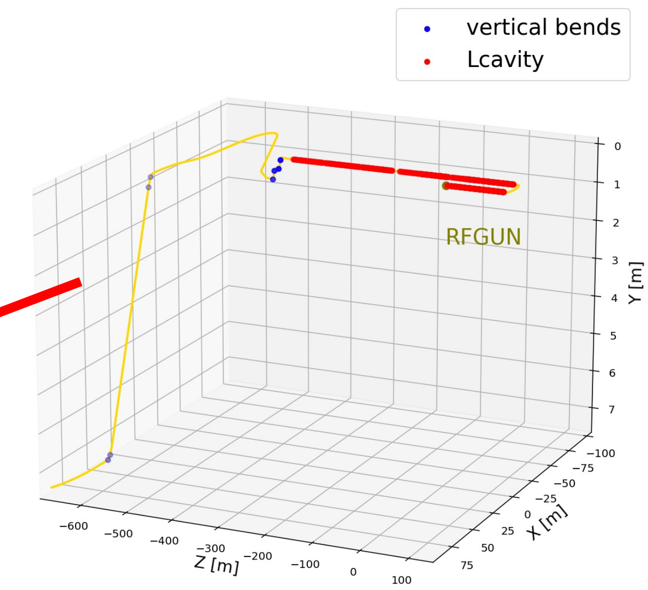
- Good polarization lifetime of ~25 minutes (~10 top-up times) with HER energy of 7.035 GeV (0.4% [i.e.+28MeV] higher than default energy) – currently using LTT to map lifetime vs energy to maximize polarization lifetime & for resonant depolarization considerations

Compact Spin Rotator provides solution to transparency with minimal changes to lattice AND ability to have SuperKEKB with no spin rotator when we do not run with polarized beams – LTT studies show minimal impact on beam & polarization lifetimes

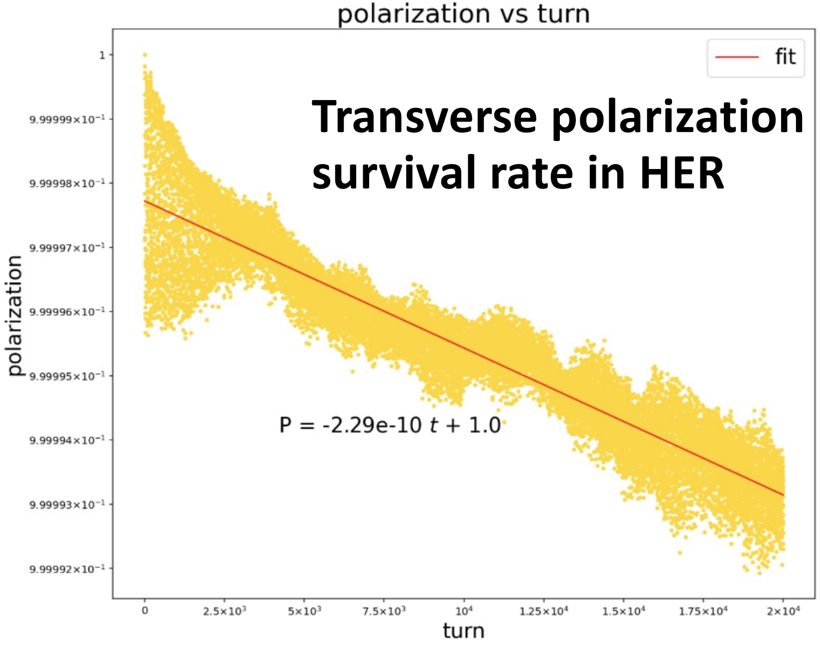
Next step: Put LTT studies to the test with data in experiment with TRANSVERSE polarized beam to validate polarization lifetime

Inject transversely polarized beam at the HER injection point

KEK Linac



Y. Peng's (UVictoria)


polarization vs turn

Transverse polarization survival rate in HER

Tracking 100 particles for 20000 turns in the HER with BMAD

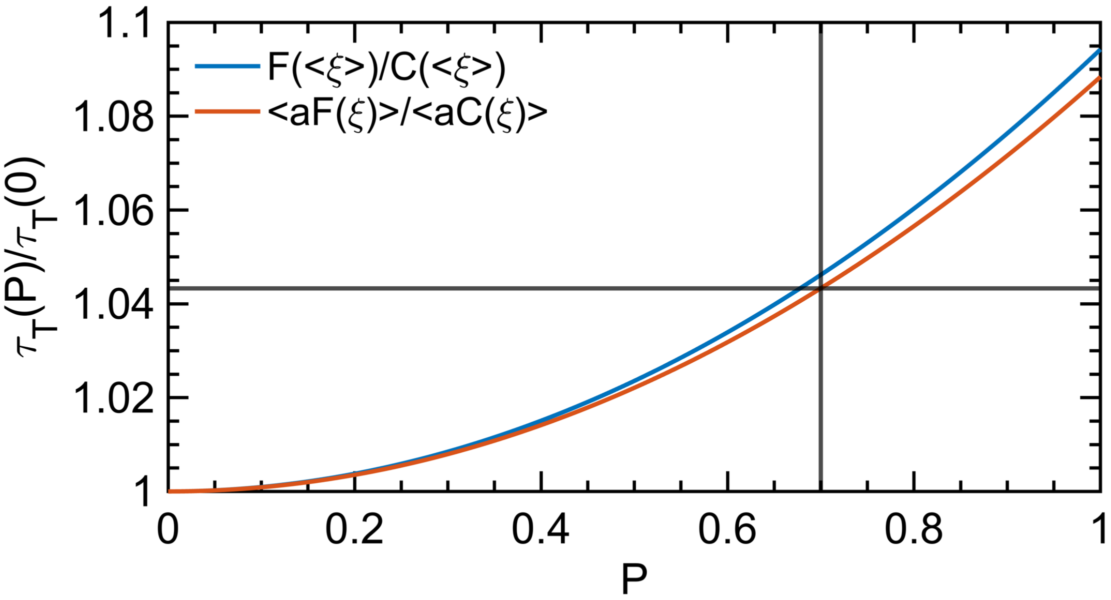
This study estimates polarization lifetime > 10 hours

History of Touschek lifetime being used to measure transverse polarization

- Touschek described the lifetime of electrons in AdA ('accumulation ring') in 1963 (Bernardini et al., Phys. Rev. Lett 10 (1963) 407)
- Baier & Khoze, pointed out that Touschek lifetime is sensitive to polarization (At. Energ. 25 (1968) 440)
- It was then use in the VEPP-2M ring to measure depolarization (and thus beam energy): Derbenev Part. Acc. 8 (1978) 115
  - Measuring the counting rate of scattered electrons
- Ex: Allowed first precision mass measurement of J/Psi (3096.93+-0.09 MeV) then superseded in 1993 (E760)
- Continously improved at VEPP-4M (KEDR at VEPP-4M: 3096.900 ± 0.002 ± 0.006 MeV): Phys. Lett 96B (1980) 214; Blinov et al., proc. of EPAC (2002) 1954

- More recently used at :
  - HIgS (DUKE): NIMA 614 (2010) 339
  - SOLEIL, NIMA 697 (2013) 1
  - Diamond Light Source, PRAB22 (2019) 122801
  - Based on expressions given in NIMA 554 (2005) 85
  - Also proposed for FCCee: arXiv1909.12245

For SuperKEKB



For 70% polarization this is a ~4% effect assuming (overall) momentum acceptance of 0.6%

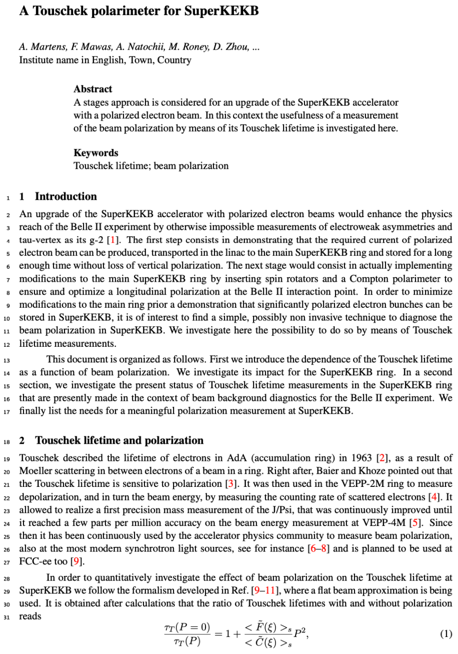
[Aurélien Martens (IJCLab) presentation in Feb 2023 B2GM and described in current draft of Chiral Belle CDR]

Touschek Lifetime Studies

Belle II Background Group has measured the Touschek Lifetime in the HER at the few per-mil level – sufficient for measuring polarization effects which are at the 4% level

Period	Experimental Touschek Lifetime (minutes)
May 2020	37.929 ± 0.057 (0.15%)
June 2020	33.656 ± 0.064 (0.19%)
June2021	27.93 ± 0.10. (0.36%)
December 2021	24.107 ± 0.079 (0.33%)

[Andrii Natochii (BNL) presentation in Oct 2023 Belle II General Meeting



A Touschek polarimeter for SuperKEKB

A. Martens, F. Mawas, A. Natochii, M. Roney, D. Zhou, ...
Institute name in English, Town, Country

Abstract
A stages approach is considered for an upgrade of the SuperKEKB accelerator with a polarized electron beam. In this context the usefulness of a measurement of the beam polarization by means of its Touschek lifetime is investigated here.

Keywords
Touschek lifetime; beam polarization

1 Introduction

An upgrade of the SuperKEKB accelerator with polarized electron beams would enhance the physics reach of the Belle II experiment by otherwise impossible measurements of electroweak asymmetries and tau-vertex as its g-2 [1]. The first step consists in demonstrating that the required current of polarized electron beam can be produced, transported in the linac to the main SuperKEKB ring and stored for a long enough time without loss of vertical polarization. The next stage would consist in actually implementing modifications to the main SuperKEKB ring by inserting spin rotators and a Compton polarimeter to ensure and optimize a longitudinal polarization at the Belle II interaction point. In order to minimize modifications to the main ring prior a demonstration that significantly polarized electron bunches can be stored in SuperKEKB, it is of interest to find a simple, possibly non invasive technique to diagnose the beam polarization in SuperKEKB. We investigate here the possibility to do so by means of Touschek lifetime measurements.

This document is organized as follows. First we introduce the dependence of the Touschek lifetime as a function of beam polarization. We investigate its impact for the SuperKEKB ring. In a second section, we investigate the present status of Touschek lifetime measurements in the SuperKEKB ring that are presently made in the context of beam background diagnostics for the Belle II experiment. We finally list the needs for a meaningful polarization measurement at SuperKEKB.

2 Touschek lifetime and polarization

Touschek described the lifetime of electrons in AdA (accumulation ring) in 1963 [2], as a result of Moeller scattering in between electrons of a beam in a ring. Right after, Baier and Khoze pointed out that the Touschek lifetime is sensitive to polarization [3]. It was then used in the VEPP-2M ring to measure depolarization, and in turn the beam energy, by measuring the counting rate of scattered electrons [4]. It allowed to realize a first precision mass measurement of the J/Psi, that was continuously improved until it reached a few parts per million accuracy on the beam energy measurement at VEPP-4M [5]. Since then it has been continuously used by the accelerator physics community to measure beam polarization, also at the most modern synchrotron light sources, see for instance [6–8] and is planned to be used at FCC-ee too [9].

In order to quantitatively investigate the effect of beam polarization on the Touschek lifetime at SuperKEKB we follow the formalism developed in Ref. [9–11], where a flat beam approximation is being used. It is obtained after calculations that the ratio of Touschek lifetimes with and without polarization reads

$$\frac{\tau_T(P=0)}{\tau_T(P)} = 1 + \frac{<\tilde{F}(\xi)>_s}{<\tilde{C}(\xi)>_s} P^2, \qquad (1)$$

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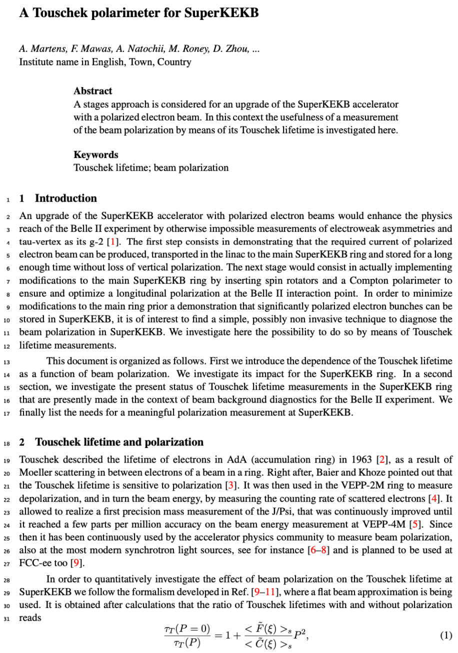

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$$\frac{\tau_T(P=0)}{\tau_T(P)} = 1 + \frac{<\tilde{F}(\xi)>_s}{<\tilde{C}(\xi)>_s} P^2, \quad (1)$$

Working with KEK source team & team members at Hiroshima, Nagoya, Victoria, BNL

Proposing 2 day experiment following SuperKEKB autumn 2025 run

- **Transverse polarization lifetime measurements with and without collisions; measure beam-beam effects on polarization**

Summary

Chiral Belle Physics Program

Unique New Physics Probe into Dark Sector via Precision measurement of weak mixing angle @ 10GeV with e, μ, τ, c and b
5x precision of EIC

Going beyond muon g-2 Measured at BNL & FERMILAB:
Tau g-2
>100x more precise than can be reached elsewhere

Worlds Highest Precision Weak Neutral Current Measurements with μ, c and b
Many times more precise than World Average of CERN & SLAC measurements
Avoids LHC hadronization uncertainties

Worlds Highest Precision Weak Neutral Current Universality Measurements with e, μ, τ, c and b many times more precise than CERN & SLAC measurements

Summary

- **Unique, High-Impact Precision Physics Program**

- **0.3% Beam polarization systematic uncertainty can be reached with both Tau Polarimetry and Compton Polarimetry**

- **Compact Spin Rotator provides solution to transparency with minimal changes to lattice AND ability to have SuperKEKB with no spin rotator (i.e. just use the dipole field) when we do not run with polarized beams – LTT studies show minimal impact on beam lifetime and polarization lifetime**

- **Next step: Put LTT studies to the test with data in experiment with TRANSVERSE polarized beam to validate polarization lifetime working with KEK source team**

Additional Information

From **KEK Roadmap 2021** (May 31, 2021)

"Other proposals for future research, such as measurements using the Belle II detector and polarized electrons requiring ***a modest upgrade to SuperKEKB****, have been made. R&D will continue to examine the technical feasibility of such projects while confirming their physics impact."*

Snowmass 2021 White Paper
Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation
arXiv:2205.12847 (Sept. 2022)

Conceptual Design Report for polarization upgrade is being drafted

Feasible to plan for installation towards end of this decade with collisions with polarization data starting while SuperKEKB completes its program of delivering 50ab^{-1} of data and continued beyond that program.

‘Chiral Belle’ → Left-Right Asymmetries

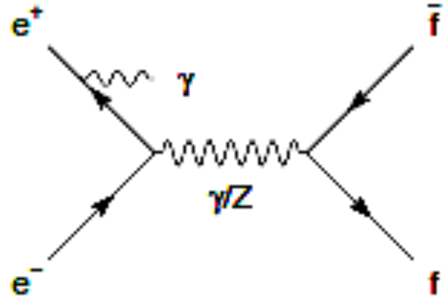
Electron helicity would be chosen for different bunch trains by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

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

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

$$\langle Pol\rangle = 0.5\left\{\left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_R - \left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_L\right\}$$

(for s-channel Born)



Source generates mainly right-handed electrons

Source generates mainly left-handed electrons

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

Compact spin rotator

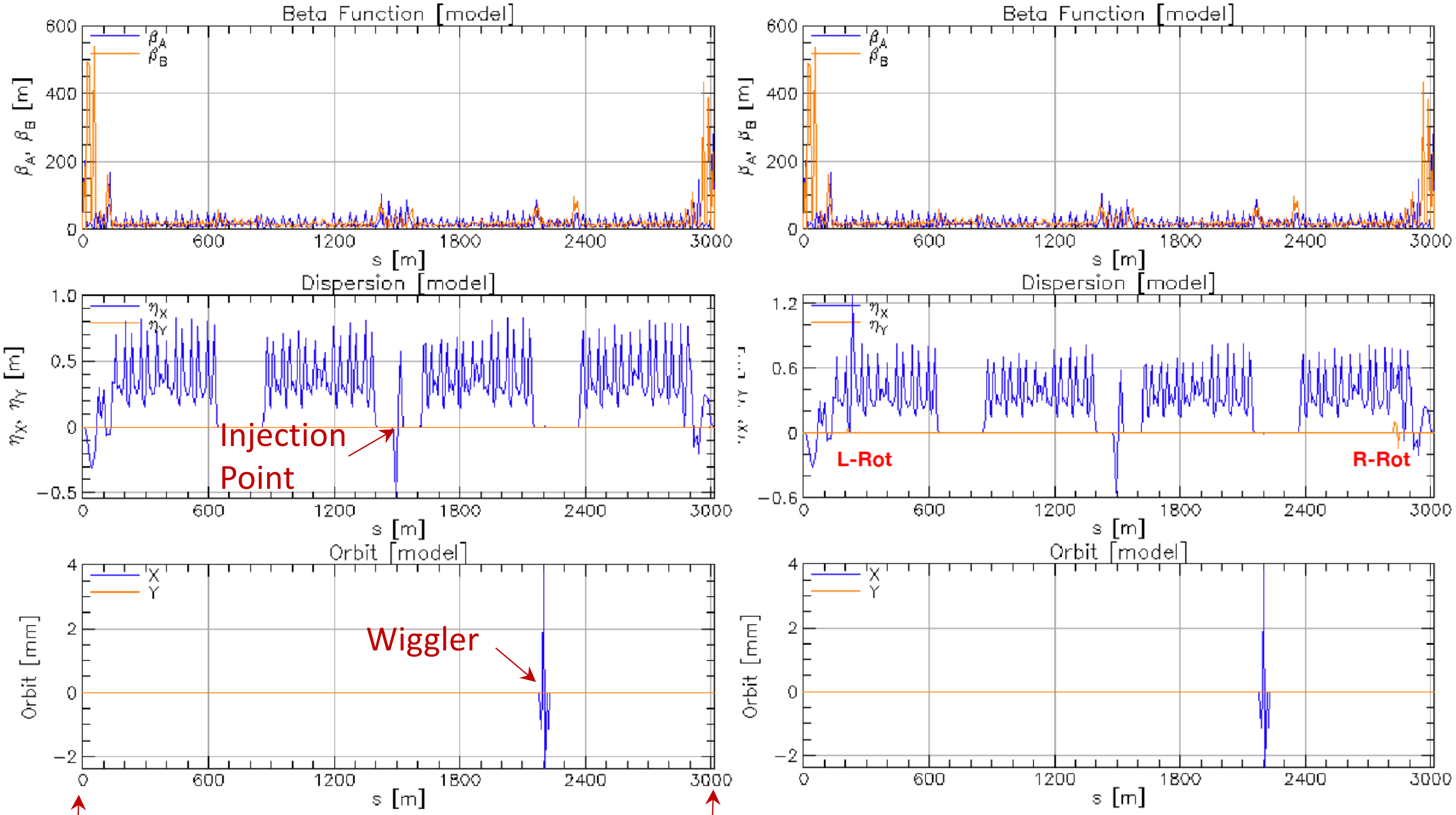
Full lattice Comparison with L/R-Rot installed & matched in the HER ring

Y. Peng (UVic) with Uli Wienands (ANL)

Beta
x & y

Diffusion
x & y

Orbit



Interaction Point

Original Ring

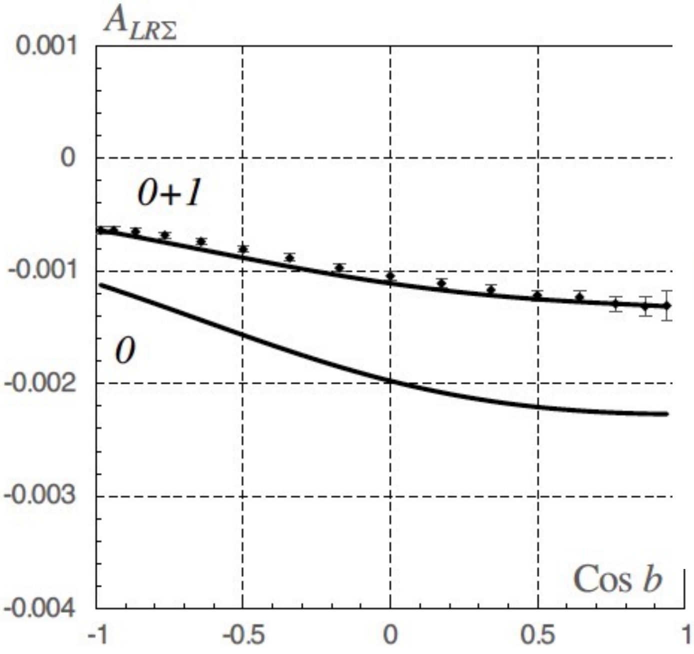
Interaction Point

Rotator Ring

Theorists currently working on SM Electroweak calculations:

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

$e^+e^- \rightarrow \mu^+\mu^-$

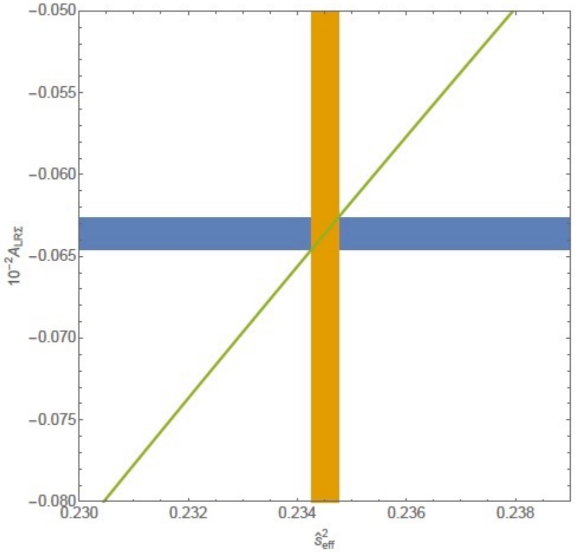


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10° & energy of photons < 2GeV

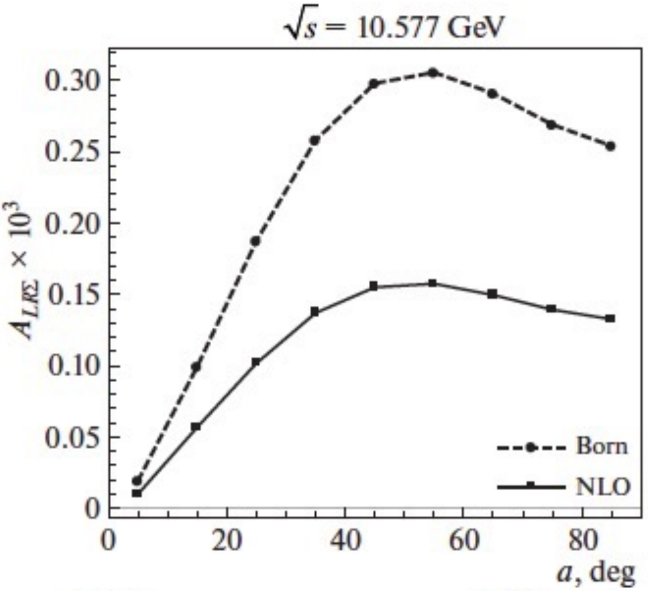
Phys.Rev. D101 (2020) no.5, 053003

$A_{LR}^{\mu\mu}$ vs $\sin^2\theta_W^{eff}$



$$A^C_{LR\Sigma} = A^C_{LR\Sigma}(a) = \frac{\Sigma_L^C - \Sigma_R^C}{\Sigma_L^C + \Sigma_R^C},$$

$e^+e^- \rightarrow e^+e^-$



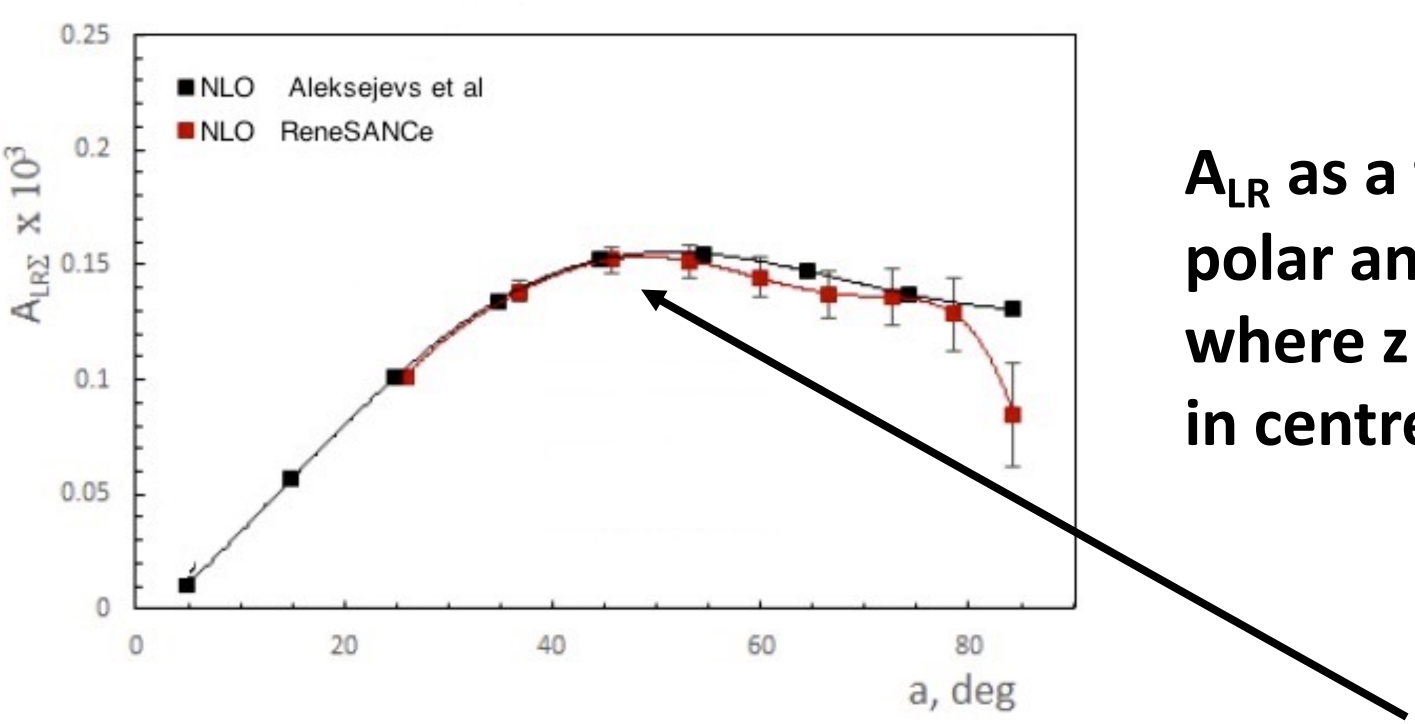
$$\Sigma_L^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{L0}^C}{dc} \cdot dc, \quad \Sigma_R^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{R0}^C}{dc} \cdot dc.$$

PHYSICS OF ATOMIC NUCLEI Vol. 83 No. 3 2020

$e^+e^- \rightarrow e^+e^-$ NLO Generator: ReneSANCe

Renat Sadykov (JINR,Dubna) and Vitaly Yermolchyk (JINR Dubna&INP,Misnk), "Polarized NLO EW e+e− → e+e− cross section calculations with ReneSANCe-v1.0.0", *Comput.Phys.Commun.* 256 (2020) 107445; 2001.10755 [hep-ph]

Relatively recently developed generator with beam polarization capable of producing Bhabhas



A_{LR} as a function of polar angle acceptance where z is e- direction in centre-of-mass

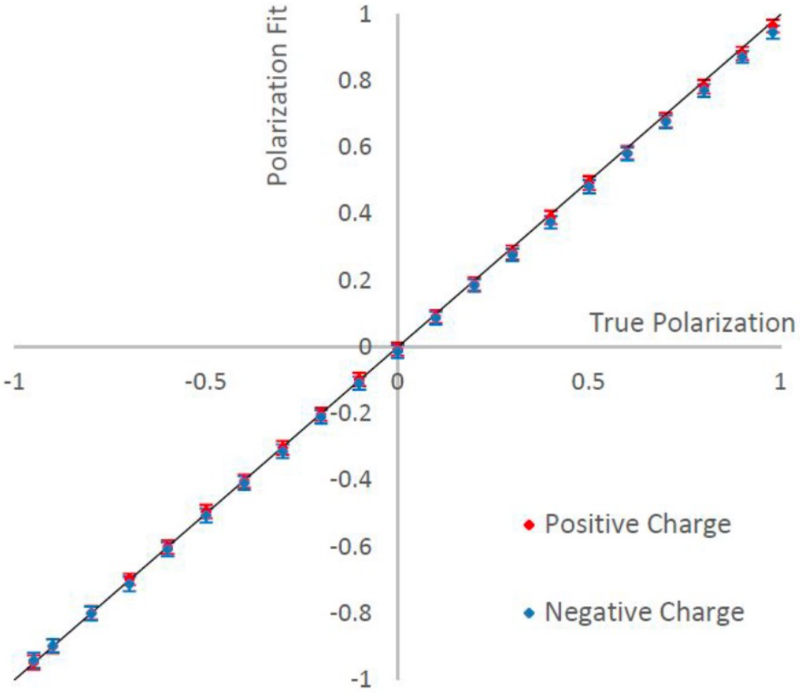
Belle II published luminosity paper with Bhabha acceptance in central part of detector:
F. Abudinén et al, Belle II Collaboration, Chin.Phys.C 44 (2020) 2, 021001
Reports: Cross-section = 17.4nb, efficiency=36%

Tau Beam Polarimetry (*BaBar* paper): e- Polarization be measured to < 0.005

https://doi.org/10.1103/PhysRevD.108.092001

Beam Polarization MC “Measurement”

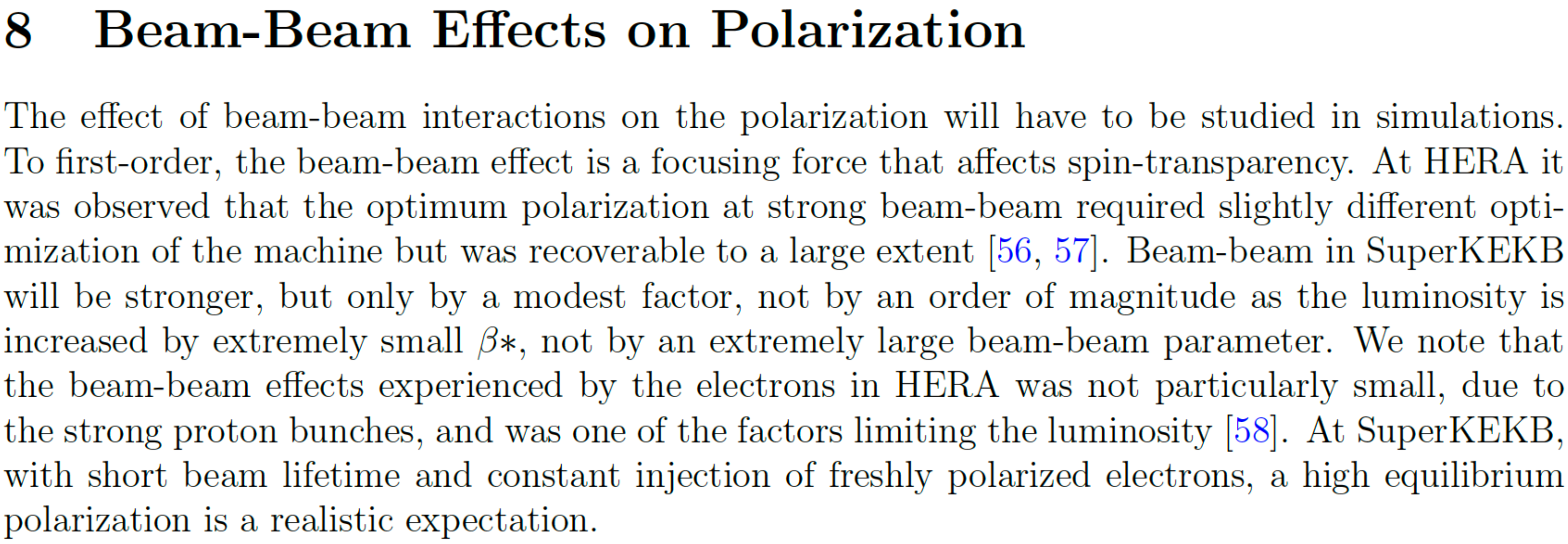
- As PEP-II had no beam polarization we performed MC studies of the polarimetry technique for arbitrary beam polarization states for validation of the method
- This is done by splitting each of the polarized tau MC samples in half
- One half of each is used to perform the polarization fit
- The other half is used to mix specific beam polarization states
    - e.g. 70% polarized = 85% left +15% right
- Simulated beam polarization states are produced in steps of 10% beam polarization
- We found the fit responded well and was able to correctly measure any designed beam state



Caleb Miller: Tau 2023 Conference

Beam-beam effects

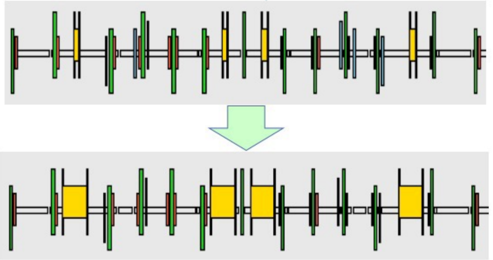
“Snowmass 2021 White Paper Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation”
April 13, 2022



8 Beam-Beam Effects on Polarization

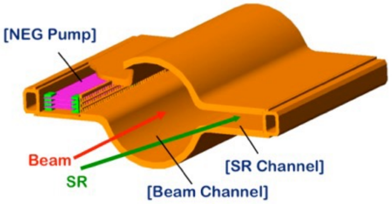
The effect of beam-beam interactions on the polarization will have to be studied in simulations. To first-order, the beam-beam effect is a focusing force that affects spin-transparency. At HERA it was observed that the optimum polarization at strong beam-beam required slightly different optimization of the machine but was recoverable to a large extent [56, 57]. Beam-beam in SuperKEKB will be stronger, but only by a modest factor, not by an order of magnitude as the luminosity is increased by extremely small $\beta*$, not by an extremely large beam-beam parameter. We note that the beam-beam effects experienced by the electrons in HERA was not particularly small, due to the strong proton bunches, and was one of the factors limiting the luminosity [58]. At SuperKEKB, with short beam lifetime and constant injection of freshly polarized electrons, a high equilibrium polarization is a realistic expectation.

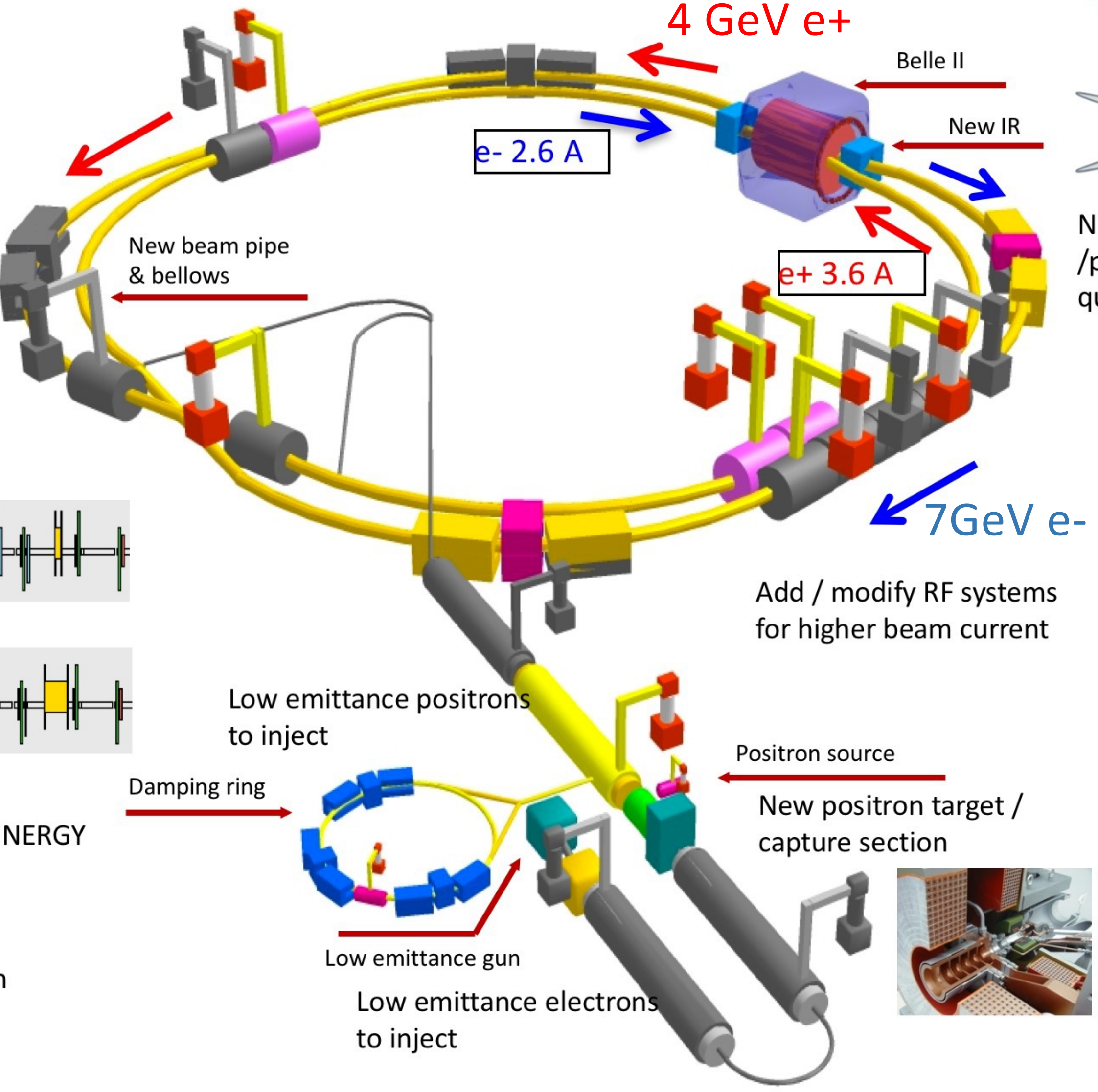
Replace short dipoles with longer ones (LER)



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

TiN-coated beam pipe with antechambers





4 GeV e+

Belle II

New IR

e- 2.6 A

e+ 3.6 A

New beam pipe & bellows

7GeV e-

Add / modify RF systems for higher beam current

Low emittance positrons to inject

Damping ring

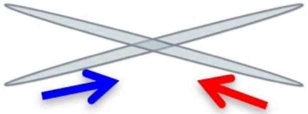
Positron source

New positron target / capture section

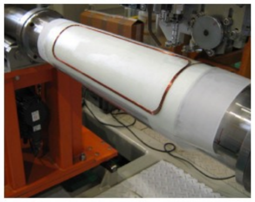
Low emittance gun

Low emittance electrons to inject

Colliding bunches



New superconducting /permanent final focusing quads near the IP



To obtain x40 higher luminosity